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Single Mode Operation of Short-Cavity Quantum Cascade Lasers*

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Abstract: Single mode operation of strain-compensated $In_{1-x}Ga_xAs/In_{1-y}Al_yAs$ quantum cascade lasers emitting at $\lambda \approx 5.4$ and 8μm is realized by shortening the Fabry-Perot cavity length. Accurate control of growth parameters and strain balance results in a perfect lattice match and thus in excellent material quality. Single mode emission with a side mode suppression ratio greater than 20dB for uncoated lasers is realized. Record low threshold currents of 50 and 80mA and record short cavity lengths of 145 and 170μm are achieved for $\lambda \approx 5.4$μm and $\lambda \approx 7.84$μm devices, respectively, in pulsed mode.

Key words: strain-compensated quantum cascade lasers; short cavity length; single mode emission
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1 Introduction

Recent work on mid-infrared quantum cascade lasers (QCLs) has produced a variety of powerful coherent emitters[1~3]. Steady improvement in the past years has enabled continuous-wave and room-temperature operation. This has made QCLs more appealing for real world applications, such as free space communications and remote chemical sensing, which demand cheap monolithic mid-infrared sources. Most of these applications require stable, single mode emission of QCLs. Distributed feedback and micro cavity resonators have been employed to produce such required emission. These techniques, however, result in inevitably complicated and prolonged fabrication processes.

Significant achievements in vertical-cavity surface-emitting lasers have helped us hit on a new idea. Single mode operation can be easily demonstrated for vertical-cavity surface-emitting lasers using Fabry-Perot microcavities with highly reflective Bragg-mirrors. Recognizing that the QCL wavelengths are in the mid-infrared range, stable single longitudinal mode operation can be achieved in QCLs by shortening the cavity length. The spacing of Fabry-Perot modes increases with the decrease of cavity length. Thus, the number of allowed oscillation modes is reduced. When the secondary modes beside the master mode pass over the range of gain bandwidth, only the master mode acquires sufficient gain to reach its threshold. Thus a short Fabry-Perot cavity provides a very elegant and simple route to achieving the required single mode operation. In this paper, we demonstrate single mode QCLs with short cavities.

2 Fabrication and measurement

The designs presented here for $\lambda \approx 5.4$ (sample G064) and 8μm (sample G044) employ a double-phonon resonant design similar to one previously published[4~6]. This four quantum-well design has a high injection efficiency due to the first thin well and a short lifetime in the lower lasing state. The thick wells also decrease scattering due to the interfacial roughness, and the relatively high barrier, made by strain-compensated InGaAs/InAlAs, effectively decreases the electron tunneling probability from the upper state to the continuum. Laser wafers were grown by solid-source molecular beam

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epitaxy on n-doped InP (Si, 2 $\times10^{17}$ cm^{-3}) substrates. The growth process started with the lower waveguide layers (InGaAs, Si, (6～8) $\times10^{16}$ cm^{-3}, 0.3～0.4μm in thickness), continued with the thirty stage of strain-compensated $In_{1-x}Ga_xAs/In_{1-y}Al_yAs$ active layers and the upper waveguide layers (InGaAs, Si, (6～8) $\times10^{16}$ cm^{-3}, 0.3～0.4μm in thickness), and was finished with thicker upper waveguide cladding and cap layers (InP, Si, 1 $\times10^{17}$ ～ 5 $\times10^{18}$ cm^{-3}, 2.5μm in thickness). The active regions of QCLs are designed as partially strain-compensated, while the remaining strain is compensated in the cladding layers. The net strain in the complete structure tends to zero.

X-ray diffraction spectra of the laser wafers are shown in Fig. 1. The excellent periodicity and narrow line-widths of the satellite peaks indicate extremely good material quality, especially good interfaces between the layers. The zero-order superlattice diffraction peaks show a perfect lattice match to the InP substrate, indicating extremely good material quality. This indicates that the laser wafers incorporating strained InAlAs and InGaAs, have been properly strain-balanced to give a net strain of zero.

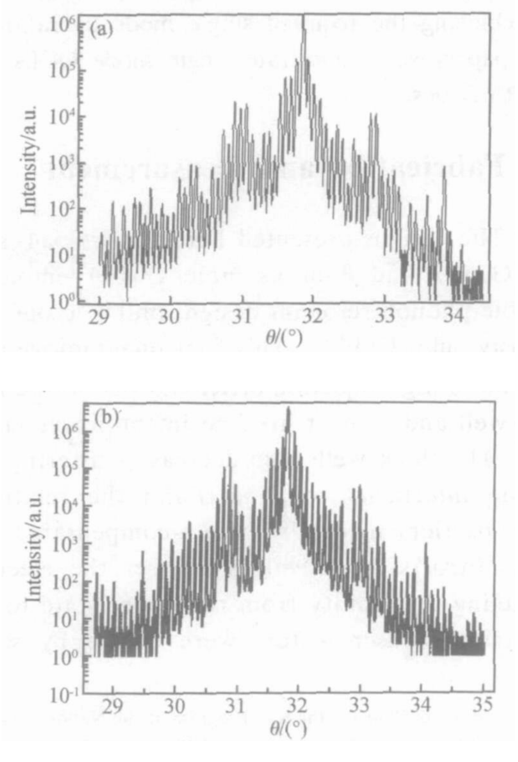

Fig. 1 X-ray diffractions of strain-compensated $In_{1-x}Ga_xAs/In_{1-y}Al_yAs$ QCLs (a) $\lambda\approx5.4$μm; (b) $\lambda\approx7.84$μm

Devices fabricated from the sample wafers were processed into ridge mesas with various widths (10～30μm) with photolithography and wet chemical etching in HBr : HNO_3 : H_2O solution. A SiN_xO_y layer with a coverage thickness of 350nm was deposited around the mesa for electrical isolation. AuGeNi/Au was used for top and bottom contacts. No annealing of the contacts was performed. The lasers were cleaved into cavities with various lengths, with the facets left uncoated for testing. All devices were tested with the epitaxial-layer-side-down bonded to Cu heat sinks in a temperature controlled (77 ～ 400K) liquid nitrogen cooled Dewar with BaF_2 windows. The devices were driven with a 1μs pulse at a 5kHz repetition rate.

3 Device performance

The spectral characteristics of the devices were tested with a Bruker Equinox 55 Fourier transform infrared spectrometer with a liquid nitrogen-cooled HgCdTe detector. To reveal the influence of cavity length on the performance of QCLs, devices fabricated from wafers G044 and G064 with different cavity lengths were cleaved. Figure 2 shows the lasing spectra of G064 QCLs with cavity lengths of 145, 290, and 390μm at 78K. The lasing wavelength is about 5.4μm. The mode spacings are 29.0, 14.5, and 10.8nm, respectively, as expected from the cavity lengths and the lasing wavelengths. The QCLs with 290 and 390μm cavity lengths show multimode spectra. However, the spectrum of the laser with a 145μm cavity length shows a distinct single mode and a full width at half maximum of only 2nm. The observed single mode is so perfect that no detectable side-modes can be caught.

The emission wavelength of a QCL can be tuned over a small range by changing the temperature. The single mode emission spectra for a 145μm-long cavity QCL (G064) at heat sink temperatures of 78, 90, 109, and 129K are shown in Fig. 3. At a fixed current of 100mA, the emission wavelength of the laser shifts form 5.47μm at 78K to 5.48μm at 129K. The single mode emission is quite stable throughout the entire temperature range. The measured single mode wavelengths are well fitted by a linear function (inset of Fig. 3) with a wavelength-temperature tuning coefficient

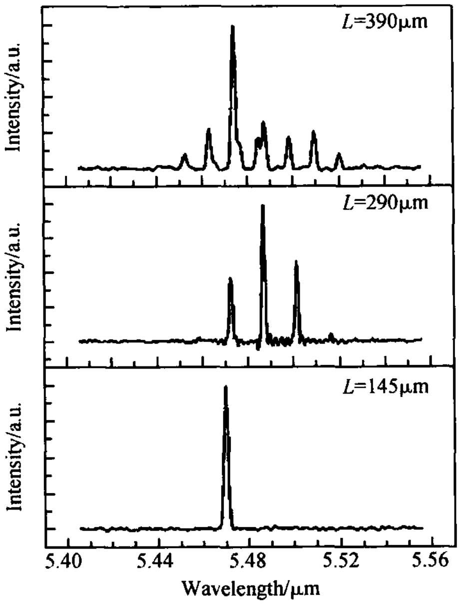

Fig. 2　Lasing spectra of 22μm wide and 145, 290, and 390μm long QCLs at 78 K　A distinct single longitudinal mode is observed for QCL with a cavity length of 145μm.

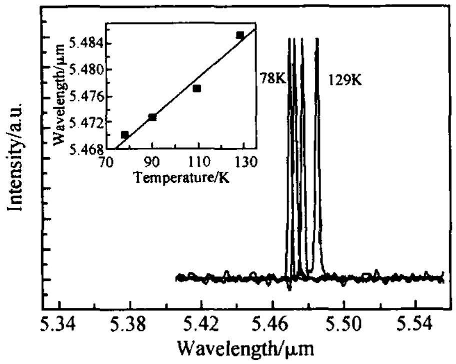

Fig. 3　Single mode emission spectra of 22μm wide and 145μm long QCL (G064) at different temperatures between 78 and 129 K　The device operates in pulsed mode (1μs, 5kHz). Inset shows the emitted wavelength dependence on temperature at a constant drive current of 100mA.

$d\lambda/dT = 2.93\times10^{-4}\mu m/K$. Due to the higher mirror loss, the maximum operation temperature is limited to about 130 K.

The output power was measured from a single laser facet using a Molectron EPM1000 power meter with a thermopile detector, which was placed 3.5cm in front of the laser facet (because of the Dewar size). No parabolic mirror or lens was used to focus the light between Dewar and detector. The output power recorded from the detector was only a portion of the true optical output of the devices due to the absorption of the optics windows (BaF_2) and the poor collection efficiency of the detector (which was limited by the laser far-field character and was calculated to be no more than 60 %). Typical values of optical power per facet versus current behavior of the uncoated QCLs (G064) with different cavity lengths at 78 K are shown in Fig. 4. The threshold currents are 50, 300, and 360mA, respectively. The corresponding powers are 3.16, 9.67, and 29.56mW, respectively. The considerable reduction in threshold current is the result of the shorter cavity length. But the mirror loss varies directly with inverse cavity length, and eventually the maximum power decreases due to the reduced emission volume and limited maximum current density.

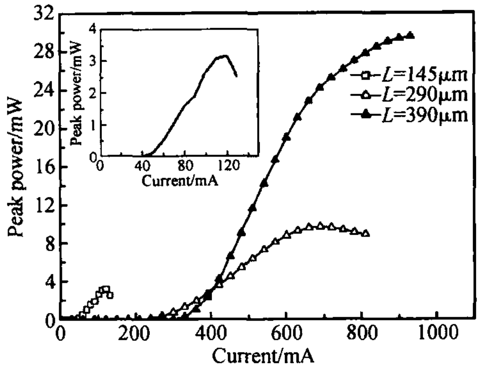

Fig. 4　Optical power from a single facet as a function of driving current for $\lambda\approx 5.4\mu m$ lasers with different cavity lengths (145, 290, and 390μm) measured at 78 K　The inset enlarges the L-I curve of 145μm long QCL.

The above mentioned single mode operation of a QCL draws attention to a clever and simple route for a micro Fabry-Perot edge emitting QCL to realize single mode operation. We also investigated the cavity-length's effects on QCLs made with sample G044 and realized single mode operation at 7.839μm. The single mode emission spectrum for a 170μm-long short cavity QCL (G044) at a heat sink temperature of 84 K is shown in Fig. 5. The device is emitting in single mode at 7.839μm with a side mode suppression ratio of 20dB limited by the intensity dynamics of the measurement setup. The single mode emission is also quite stable.

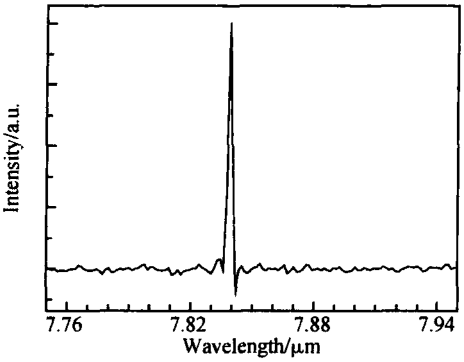

Fig. 5 Single mode emission spectrum of QCL (G044) 22μm in width and 170μm in length at 84K

4 Conclusion

In summary, we report the fabrication and characterization of short cavity single mode QCLs at $\lambda \approx 5.4\mu m$ and $\lambda \approx 7.84\mu m$. The first and shortest operating micro QCL has a cavity length of 145μm which is, to our knowledge, the shortest edge emitting QCL realized. Our work is intended mainly to open a simple and feasible route to achieve the necessary single mode operation. On the basis of high quality strain-compensated InGaAs/InAlAs materials, this main goal is achieved by shortening the cavity length. Record low values of a threshold current of 50mA for a $\lambda \approx 5.4\mu m$ uncoated device with a cavity length of 145μm, and 80mA for a $\lambda \approx 7.84\mu m$ uncoated device with a cavity length of 170μm have been achieved in pulsed mode at liquid nitrogen temperature. This fascinating feature of QCLs may promote their potential applications.

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短腔长单模量子级联激光器 *

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摘要: 报道了激射波长为5.4和7.84μm的应变补偿 $In_{1-x}Ga_xAs/In_{1-y}Al_yAs$ 量子级联激光器的单模激射. 以高质量的应变补偿量子级联激光器材料为支撑,通过减小FP腔长,开辟实现单模器件的新途径. 首次实现阈值电流仅为50mA、腔长为145μm的激射波长在 $\lambda \approx 5.4\mu m$ 的单模激射和阈值电流仅为80mA、腔长为170μm的激射波长在 $\lambda \approx 7.84\mu m$ 的单模激射. 这是目前InGaAs/InAlAs材料体系最短腔长的边发射量子级联激光器.

关键词: 应变补偿量子级联激光器; 短腔长; 单模激射

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