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Room Temperature Operation of Strain-Compensated 5.5μm Quantum Cascade Lasers*

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Abstract: Room temperature operation is an important criterion for high performance of quantum cascade lasers. A strain-compensated quantum cascade laser ($\lambda \approx 5.5\mu m$) with optimized waveguide structure lasing at room temperature is reported. Accurate control of layer thickness and strain-compensated material composition is demonstrated using X-ray diffraction. An output power of at least 45mW per facet is realized for a 20μm-wide and 2mm-long laser at room temperature.

Key words: quantum cascade laser; molecular beam epitaxy; lasing performance
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1 Introduction

The quantum cascade lasers (QCLs) designed through band-structure engineering and grown by molecular beam epitaxy (MBE), have obtained great achievement since their first demonstration in 1994[1~4]. In particular, QCLs in the 3~8μm spectral range have made great progress[5] because of their potential applications, such as trace gas sensing, medical diagnosis, and optical free-space communication[6]. Some of them have been used for chemical detection experiments[7]. Room temperature operation is necessary for all these applications, and it's also an important criterion for QCL high performance. For the purpose of room temperature operation, the strain-compensation technique, as the most effective method, is an absolutely necessary means recently adopted in QCL structure design and material growth. The strain-compensated material system can not only give an enlarged conduction band discontinuity but also make the control of material quality easier by adjusting the alloy compositions and balancing the tensile strain and compression strain. In this paper, we report the room temperature operation of $\lambda \approx 5.5\mu m$ strain-compensated QCLs incorporating optimized structures and high quality materials.

2 Structure optimizing and materials characteristic

The strain-compensation technique used in our structure has been the first choice for high performance QCLs since the pioneering work of Liu *et al.*[8,9]. This effective method results in perfect material quality and high performance due to a larger conduction band discontinuity[10]. We use InP as a waveguide material instead of InGaAs and InAlAs in order to improve the heat dissipation of the device, a main obstacle to the development of the QCL, because the thermal conductivity of InP is about 10 times higher than that of InGaAs and InAlAs (Figure 1). Furthermore, the refractive in-

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dex of InP, $n_{InP} \approx 3.10$, is less than that of InAlAs (3.20) and InGaAs (3.49), allowing for a larger refractive index step between the core and the cladding layers.

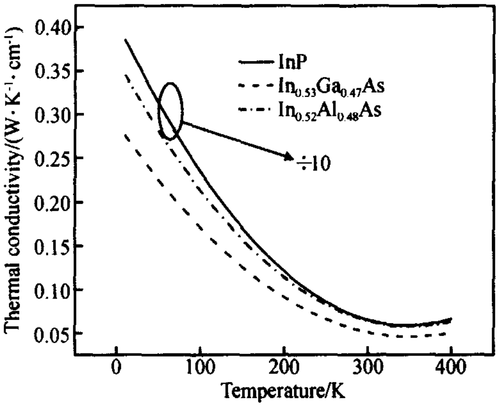

Fig. 1 Calculated thermal conductivity of InP, InGaAs, and InAlAs meterials using $4.06 - 0.020T + 2.88 \times 10^{-5} T^2$ for InP, $0.29 - 0.00139T + 1.98 \times 10^{-6} T^2$ for $In_{0.53}Ga_{0.47}As$[11], and $1.25 \times 0.29 - 0.00139T + 1.98 \times 10^{-6} T^2$ for $In_{0.52}Al_{0.48}As$[12]

The laser wafer was grown by MBE on n-doped InP substrate in a solid-source MBE system. The active region consists of 30 stages, which are alternating n-doped injector regions and undoped coupled well active regions using an $In_{0.6}Ga_{0.4}$-As/$In_{0.4}Al_{0.6}As$ material system. The structure is similar to that of Ref. [13]. The detailed structure including the waveguide is illustrated in Fig. 2.

InGaAs	400nm	$5 \times 10^{18} cm^{-3}$
InP	2500nm	$5 \times 10^{18} cm^{-3}$ ↑ $1 \times 10^{17} cm^{-3}$
InGaAs	350nm	$1 \times 10^{17} cm^{-3}$
(Active + Injector)	30 ×	
InGaAs	300nm	$1 \times 10^{17} cm^{-3}$
InP substrate		n-doped

Fig. 2 Schematic cross section of the complete InGaAs/InAlAs/InP laser structure grown by MBE

The double X-ray diffraction spectrum of the whole structure was used to evaluate the wafer quality before the device processing (Fig. 3). The excellent periodicity and narrow linewidths of the satellite peaks shown in Fig. 3 indicate extremely good quality of the material, especially good interfaces between the superlattice layers. The mismatch of the structure can be calculated from the results of the X-ray experiment by

$$m = \frac{\delta a}{a} = -\delta\theta \cot\theta \tag{1}$$

where a is the lattice constant, δa is the difference between the substrate and the epilayer, and θ is the substrate Bragg diffraction angle, which can be calculated using Bragg's equation, $2d\sin\theta = n\lambda$. A rocking curve was recorded for the (004) reflections from the sample, so d is the identity distance of (004). Finally, $\delta\theta$ is the difference of Bragg diffraction angles between the substrate and epilayer. The zero-order peak of Fig. 3 shows a nearly perfect overlap with the diffractive peak of the InP substrate, which indicates that the whole QCL structure, made from strained $In_{0.4}Al_{0.6}As$ and $In_{0.6}Ga_{0.4}As$, has been almost properly strain-balanced to give a net strain of nearly zero.

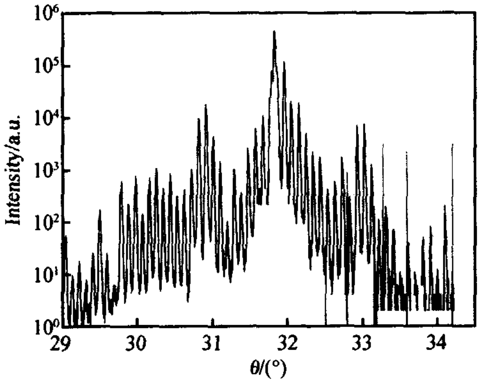

Fig. 3 X-ray diffraction spectrum for a 30 period InGaAs/InAlAs QC laser structure

The thickness of a single layer cannot be determined from the result of the X-ray diffraction because of the complicated diffraction interaction due to the periodic multistage structure of QCLs and the limited range of measurement, but the thickness of one period can be calculated using Eq. (2).

$$t = \frac{1}{m} \times \sum_{m} \left| \frac{L_j - L_i}{2(\sin\theta_j - \sin\theta_i)} \right| \tag{2}$$

where L_i and L_j are two different diffraction orders, and θ_j and θ_i are the corresponding diffraction angles. The calculated thickness of one period of our structure from the result of the double X-ray experiment is 51.87nm, which is very close to the designed value of 51nm.

3 Device fabrication and characteristics

Photolithography and wet chemical etching in a $HBr:HNO_3:H_2O$ solution were used to process lasers into 20μm strips. After the ridge waveguide was etched, a SiO_2 layer was grown by chemical vapor deposition to provide insulation between the contact pads and the n^{++}-InGaAs layer. After opening a window into the insulation for current injection, non-alloyed Ti/Au ohmic contacts were deposited on the top layer and the substrate. The devices were then cleaved into laser bars leaving the facet uncoated, and then soldered, epilayer-down, to copper holders using indium and wire bonded together.

After soldering, the heat sinks were placed in a liquid nitrogen cryostat, and the spectra were measured with a BRUKE EQUINOX 55/S step scan Fourier transform infrared (FTIR) spectrometer and a liquid nitrogen cooled HgCdTe detector. Figure 4 shows the lasing spectra of the device with a duty cycle of 1% and a repetition rate of 5kHz at room temperature and 83K. The lasing wavelength is 5.49μm at room temperature. The line width of room temperature spectrum is somewhat wider than that of 83K. Moreover, the intensity of the room temperature spectrum is weaker than that at 83K. When keeping the heat sink temperature fixed while increasing the driving current, no detectable wavelength shift was observed. The emission intensity increases almost linearly with the driving current (inset of Fig. 4), indicating that there is no obvious rise in core temperature resulting from the increase of the current under this pulse width. This attests to the good heat dissipation of our devices, which is due to the use of InP as a cladding layer.

The measurement of optical power at room temperature was done in atmosphere on a copper mount using 2μs-long driving current pulses at a 5kHz repetition rate. The optical power emitted from a single facet of the laser was measured with a thermopile detector placed near the facet of the laser. The *L*-*I* curves of pulse operation at room temperature are shown in Fig. 5. An optical output power as high as 45mW per facet was obtained at room temperature for an uncoated device. This is one of the best results ever reported.

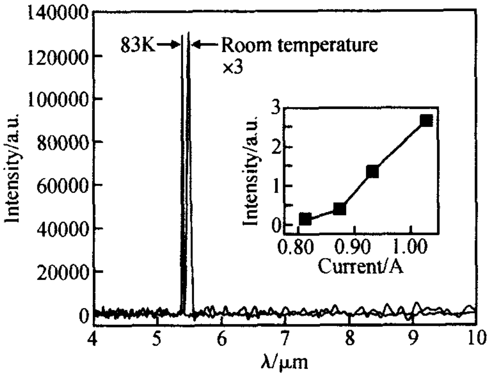

Fig. 4 Emission spectrum measured with a duty cycle of 1% and a repetition of 5kHz at room temperature The driven current is 1.031A. Inset: the spectrum intensity and current curve obtained with a fixed heat sink temperature.

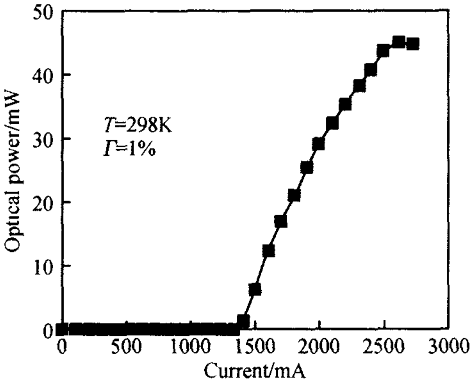

Fig. 5 Light-current (*L*-*I*) characteristics at room temperature from a single laser facet The device is driven in pulse mode with a pulse width of 2μs and a repetition of 5kHz.

4 Conclusion

In summary, we report the room temperature lasing performance of strain-compensated InGaAs/InAlAs/InP QCLs grown by MBE. A double X-ray diffraction experiment is used to test the structure and quality of material. An output power of at least 45mW per facet is realized for an uncoated 20μm-wide and 2mm-long laser at room temperature.

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室温激射应变补偿5.5μm量子级联激光器*

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摘要: 利用应变补偿和优化波导结构来提高量子级联激光器的性能,实现了波长为5.5μm量子级联激光器的室温激射. 利用双晶X射线衍射实验对材料生长质量进行了检验. 对于条宽为20μm,长为2mm的脊形波导激光器,室温最大输出功率为单腔面45mW.

关键词: 量子级联激光器; 分子束外延; 激光器性能

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