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Quasi-continuous-wave operation of AlGaAs/GaAs quantum cascade lasers

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Abstract

Quasi-continuous-wave operation of AlGaAs/GaAs-based quantum cascade lasers ($\lambda \sim 9\,\mu m$) up to 165 K is reported. The strong temperature dependence of the threshold current density and its higher value in high duty cycle is investigated in detail. The self-heating effect in the active region is explored by changing the operating duty cycles. The degradation of lasing performance with temperature is explained.

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Keywords: Injection efficiency; Molecule beam epitaxy (MBE); Quasi-continuous-wave; Quantum cascade lasers (QCLs); Self-heating effect

1. Introduction

In recent years, AlGaAs/GaAs is the most attractive material system following InGaAs/InAlAs/InP for the fabrication of quantum cascade lasers (QCLs) [1–3] due to the possibility of low-loss waveguide designs [4] and the crucial role in obtaining population inversion in the terahertz region [5]. The performance of AlGaAs/GaAs-based QCLs has been improved dramatically by optimizing the material quality and processing technology [6–9]. Although there are many achievements in AlGaAs/GaAs QCLs in the last several years, the performance of devices, such as the CW-operation temperature, the threshold current density, and the wall-plug efficiency, is inferior to their counterpart, InGaAs/InAlAs/InP ones. It is necessary to disclose the performance evolution with temperature for GaAs-based QCLs. However, the corresponding investigation on these devices operating in higher duty cycle which may induce the self-heating effect in the active region is lacking. In this paper, we investigate the degradation characteristic of the AlGaAs/GaAs QCLs in quasi-continuous-wave operation in detail and expect to give a clue to improve the performance of devices in the future.

2. Material growth and device processing

The QCL structure demonstrated in this paper was based on the so-called three-quantum-well active region very similar to the one presented in Ref. [6] and was described in Ref. [10]. All layers were grown on n-doped (Si, $2 \times 10^{18}\,cm^{-3}$) GaAs substrate by molecule beam epitaxy (MBE) in a single growth step. The growth started with $1\,\mu m$ highly doped (Si, $6 \times 10^{18}\,cm^{-3}$) GaAs waveguide, followed by the waveguide core which consists of 30 stages of injector/active regions ($\sim 1.4\,\mu m$ thick) and is sandwiched between two $3.75\,\mu m$ low-doped (Si, $4 \times 10^{16}\,cm^{-3}$) GaAs cladding material. Finally, a $1\,\mu m$ highly doped (Si, $6 \times 10^{18}\,cm^{-3}$) GaAs was grown as the top cladding and contacting layer.

The wafer was processed into double-channel ridge devices with different ridge widths (35, 45, and $55\,\mu m$) by reactive ion etching into a depth penetrating through the waveguide core. A 300-nm-thick SiO_2 layer was then grown by chemical vapor deposition for insulation around

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the ridges. For current injection, windows were opened through the insulator on top of the ridge with widths of 15, 25, and 35 μm, respectively. Nonalloyed Ti/Au Ohmic contacts were provided to the top layer. After the wafer was thinned down to about 100 μm, an alloyed AuGe/Ni/Au contact was deposited on the backside. The lasers were cleaved in bars of 2 mm length and soldered epilayer down on copper holders, and then wire bonded.

For characterization, lasers were mounted on a temperature-controlled cold finger in an evacuated liquid nitrogen cryostat. The spectral measurements were carried out with a Fourier transform infrared (FTIR) spectrometer in the step-scan mode. The optical output power emitted from a single facet of the lasers was measured with a calibrated thermopile detector placed near the window of the cryostat. The *V–I* characteristic was given by a synchronous oscilloscope.

3. Results and discussion

Fig. 1(a) shows the light-output and voltage versus injection current *L– V–I* at various heat sink temperatures of a 45-μm-wide and 2-mm-long laser. The threshold current density versus temperature is also shown. A quasi-continuous-wave (1 kHz and 1% duty cycle) optical output power as high as 210 mW is obtained at 83 K with a threshold current density (J_{th}) of 4.44 k A cm^{-2} and a slope efficiency (η) of 93.9 mWA^{-1}. At 103 K, the output power is 30 mW and J_{th} is 5.79 k A cm^{-2}, and η is 24.2 mW^{-1}A. The output power is not corrected by the transmission of optics windows (BaF$_2$, the transmission efficiency is about 92% for the wavelength about 9 μm) and the collection efficiency of the detector (limited by the laser far-field and calculated to be about 60%). Shown in the *V–I* curves, the threshold voltage (V_{th}) is 8.41 and 9.7 V with the series resistance 1.19 and 1.29Ω at 83 and 103 K, so the injection power arrives near 33.6 and 51 W, respectively, at the threshold. From the inset of Fig. 1(a), a strong dependence of the threshold current density on the heat sink temperature can be observed. The solid line is the fitting with the exponential function $J_{\mathrm{th}} = J_0 \exp(T/T_0)$. From the result of the fitting, the laser exhibits a characteristic temperature T_0 about 77 K.

As shown in Fig. 1(b), the slope efficiency behaves with a trend of degradation at a higher rate, especially when the temperature exceeds 88 K. The slope efficiency per facet can be expressed as [11]

$$\eta = \frac{\mathrm{d}P}{\mathrm{d}I} = \frac{1}{2}\frac{h\nu}{e} N_P \frac{\alpha_{\mathrm{M}}}{\alpha_{\mathrm{M}} + \alpha_{\mathrm{W}}} \eta_{\mathrm{i}} \eta_{\mathrm{coll}}, \tag{1}$$

where $h\nu$ is the photon energy at the lasing wavelength, e is the elemental electronic charge, N_P is the number of stages, α_{M} is the mirror loss, α_{W} is the waveguide loss, η_{i} is the injection efficiency, and η_{coll} is the collection efficiency. With the other parameters almost constant in this temperature range, the injection efficiency η_{i} decreases linearly with the increase of temperature. From the inset of Fig. 1(b), the maximum power conversion efficiency (double facets and including the collection efficiency) of 1% is achieved at 83 K and an injection current about 6.4 A. As the temperature increases, the power conversion efficiency drops quickly. This is to say, the great mass of electrical power over 99% is consumed in thermal dissipation. The appearance of the maximum of power conversion efficiency at each temperature results from the saturation of optical output power with the increase of the injection current.

The higher threshold current density at different temperatures may be ascribed to three main aspects: (1) electrons leakage triggered by thermal activation [12]; (2) infrared absorption induced by the dielectric material (SiO$_2$) and scattering from the edges of the ridge [13]; (3) mounting quality of laser bars. The thermal activated electrons leakage from the excited state of laser transition to continuum level boosts up with temperature. It is the primary cause for the temperature dependence of the injection efficiency. The upper inset of Fig. 2 shows is the SiO$_2$ absorption in the infrared region at room temperature and lower is threshold current density versus ridge width. The increase of threshold current density with the decrease of ridge width indicates that the quality of the surface of the wall of the ridge has a larger effect on the thermal behavior of the relatively narrower devices. Both the absorption of SiO$_2$ and the scattering of the rough surface of the ridge wall increase the lateral waveguide loss for the deeply etched devices. Fig. 2 also shows that a good quality of soldering decreases the threshold current of the laser with the same size as that demonstrated in Fig. 1. This is which mainly due to the uniform and massive nature of the solder (indium), which results in better thermal conductance and lower additional power consumption.

Fig. 3 shows the average power and threshold current density versus duty cycle at 83 K. During this experiment, the frequency of the driving current was held 1 kHz. The maximum of average power appears at duty cycle about 2%, and above this value the average power decreases linearly. The inflexion in the curve of the average power versus duty cycle indicates that the degradation of the injection efficiency will come forth at the duty cycle near 2%, which induces the strong thermal accumulation in the active region. The threshold current density increases with duty cycle and there is a different rate at the different direction of 2% duty cycle. The relation between the threshold current density and duty cycle is similar to the one between the threshold current density and the heat sink temperature. This indicates that there is a strong self-heating effect in the active region during the high duty cycle operation of these devices. By comparing the inset of Fig. 1 and Fig. 2, we can deduce that a laser operating in 5% duty cycle at the heat sink temperature of 83 K has a similar threshold current density to the same laser operating in 1% duty cycle at the heat sink temperature of 98 K. The