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Terahertz quantum cascade lasers operating above liquid nitrogen temperature

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Abstract. The development of quantum cascade lasers at 2.94 -3.10 THz are reported. The materials were prepared by Veeco GEN-II solid source molecular beam epitaxy and devices were processed using standard photolithography and wet chemical etching. Lasing is observed up to a heat-sink temperature of 80 K in pulsed mode with peak light power of 14 mW at 10 K and 2 mW at 80 K.

1. Introduction

The invention of quantum cascade laser (QCL) blazed a new way in the development of coherent laser sources in THz frequencies[1]. Since the first demonstration, significant improvements have been made over the past few years. Recently, the available highest operating temperature is 186K in pulse mode [2] and 117K in continuous-wave (CW) mode [3], the highest output peak power is 248 mW in pulse mode and 138 mW in CW mode at 10 K [4], the lowest threshold current density is 110A/cm² at 10 K [5], and the longest lasing wavelength is 250 μ m [6]. However, for the final sake of continuous wave operation at room temperature, there still much to be desired. Nowadays, a practical way is to stably operate above liquid nitrogen temperature. Here, we report the development of terahertz quantum cascade lasers about 3 THz. The chirped superlattice active region based on GaAs/Al_{0.15}Ga_{0.85}As builds bound-to-continuum transition. The materials were prepared by Veeco GEN-II solid source molecular beam epitaxy (MBE) and devices were processed using standard photolithography and wet chemical etching. The quantum cascade lasers operate about 2.94~3.10 THz due to the growth uncertainties for different wafers. For the 3.10 THz quantum cascade laser, optical powers of 14mW at 10 K and 1.5mW at 80 K are observed from a 180- μ m-wide and 2-mm-long device with a pulsed mode of 1% duty cycle. These results are an encouraging step towards a widely applicable solid-state terahertz source operating above liquid nitrogen temperature.

2. Page Device structure and fabrication processing

The structure labeled G355 and G394 were grown by EPI Gen II solid source molecular beam epitaxy on a semi-insulating (SI) GaAs substrate. The growth started with 0.8 μ m highly-doped (Si, 2.5×10^{18}

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cm^{-3}) GaAs cladding, followed by 120 periods of active regions unit, which is demonstrated in reference [7]. Finally, a $0.2\ \mu\text{m}$ highly-doped (Si , $5 \times 10^{18}\ \text{cm}^{-3}$) GaAs was grown as the top contact layer. The highly-doped GaAs cladding could provide a strongly confined low loss TM mode bound to that layer and make it easy to use the n+ layer for electrical contacting. During the growth, a substrate temperature of $580\ ^\circ\text{C}$, an arsenic overpressure of 3×10^{-6} Torr and a V/III ratio of as large as about 12 are selected.

After growth, samples were processed into $180\text{-}\mu\text{m}$ -wide ridge stripes by optical lithography and wet chemical etching ($\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:H}_2\text{O}=1\text{:}1\text{:}6$, $22\ ^\circ\text{C}$) to the bottom contact layer. The top electrical contact was provided by two $20\text{-}\mu\text{m}$ -wide stripes of Ge/Au/Ni/Au ($26/54/15/100\text{nm}$) deposited along the edges of each ridge. Two bottom $220\text{-}\mu\text{m}$ -wide contacts were evaporated on both sides of the ridge stripes with $55\text{-}\mu\text{m}$ -wide separations between the metal on the side and the edge of the ridge. The top and bottom contacts were formed by a standard lift-off deposition at the same time. Thermal annealing for 20s at $390\ ^\circ\text{C}$ under nitrogen atmosphere was followed to provide Ohmic contact. After that, Ti/Au ($8.6/200\text{ nm}$) was deposited completely covering both the bottom contact and the top of the ridge to provide the top confinement and allow for wire bonding. Then, the substrate was thinned down to $200\ \mu\text{m}$ and Ti/Au ($25/250\text{ nm}$) contact was deposited on the backside allowing for easy soldering. Finally, the sample was cleaved into laser bars with different length and $\text{Al}_2\text{O}_3/\text{Ti}/\text{Au}$ layers ($100/10/100\text{nm}$) were evaporated on the back facets to form a high reflectivity (HR) coating.

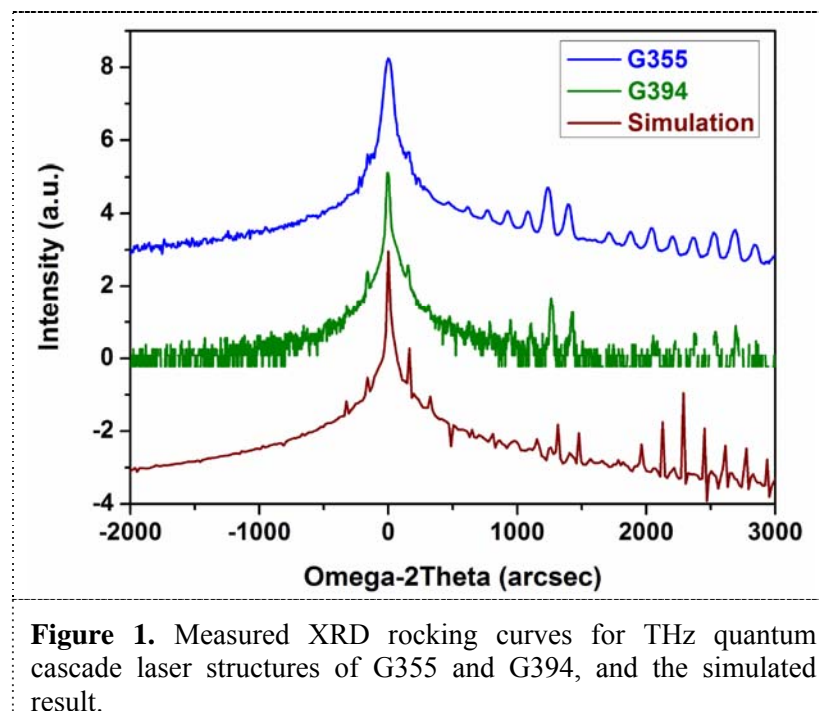


Figure 1. Measured XRD rocking curves for THz quantum cascade laser structures of G355 and G394, and the simulated result.

Double crystal X-ray diffraction (XRD) is used to analyze the periodicity of the wave-guide core [8]. Fig.1 shows the measured XRD rocking curve of G355 and G394 together with the simulated result. The actual period extracted from the XRD results are 120.79nm and 119.66 nm for G355 and G394 respectively, which show deviations about 3.95% and 2.98% from the design value. A FWHM of about 68 arcsec is shown for the satellite peak of G355 and 40 arcsec for G394.

For a comprehensive understanding about the device processing, the scanning electron microscopic image of device structure and its cross-section are shown in Fig. 2 (a) and Fig. 2(b) respectively.

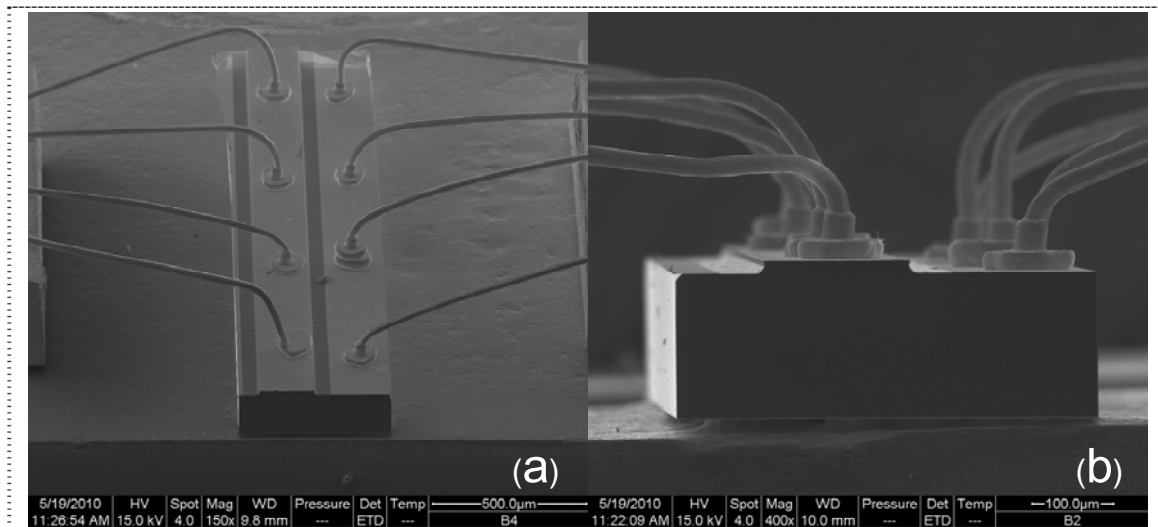


Figure 2. The scanning electron microscopic image of a laser bar: (a) the surface and (b) the cross-section.

3. Experiments and results

For device characterization, the samples were soldered epilayer up onto Cu heat-sinks with In and wire bonded. The packaged laser bars were then mounted to the cold finger of a He flow cryostat with polyethylene windows. The pulsed light power was measured by a calibrated thermopile powermeter placed directly near the polyethylene window without any accessorial optical component in the optical path. The collection efficiency was estimated to 20% in view of the beam divergence and the transmittance of the polyethylene window. For the spectral measurement, the emission was collected by two sequential off-axis parabolic mirrors, passed through a Fourier-transform infrared spectrometer and focused again onto a room temperature DTGS detector. All laser spectra were collected in rapid scan mode with a resolution of 0.5 cm^{-1} .

Fig. 3 shows the lasing spectra of G355 and G394 at a heat-sink temperature of 10 K. The laser spectra were measured with current pulses of $1\text{-}\mu\text{s}$ duration and 100-kHz frequency at about 1.2 times threshold current. The lasing frequency is 2.94 THz for G355 and 3.10 THz for G394 at 10 K, which is in accordance with the XRD results.

Fig. 4 displays the optical power versus drive current (L - I) curves for G355 at various heat-sink temperatures with current pulses of $1\text{-}\mu\text{s}$ duration and 20-kHz frequency. Lasing is observed up to 70 K with power level of 1 mW, compared to 4.75 mW observed at 10 K. The slope efficiencies are 4.72 and 1.25 mW/A for 10 K and 70 K respectively. The threshold current density as a function of temperature for the same device is plot in Fig. 4. The threshold current densities are $J_{th}=296.5 \text{ A/cm}^2$ at 10 K and $J_{th}=428 \text{ A/cm}^2$ at 70 K, and the characteristic temperature is extracted to be $T_0=57.5 \text{ K}$.

Fig. 5 displays the optical power versus drive current (L - I) curves for G394 at various heat-sink temperatures with current pulses of $1\text{-}\mu\text{s}$ duration and 10-kHz frequency. Fig.5 (a) is L - I characteristics for a 1.5-mm-long device and Fig. 5(b) for a 2-mm-long one. The two devices are all lasing up to 80 K with power level of 2 mW and 1.5 mW at 80 K. The peak powers at 10 K are 9 mW and 14 mW for the 1.5-mm-long device and the 2-mm-long one respectively. The threshold current densities $J_{th}=370 \text{ A/cm}^2$ at 10 K and $J_{th}=667 \text{ A/cm}^2$ at 80 K for the 1.5-mm-long device, and $J_{th}=685 \text{ A/cm}^2$ at 10 K and $J_{th}=1260 \text{ A/cm}^2$ at 80 K for the 2-mm-long one. The characteristic temperatures are extracted to be $T_0=31.5 \text{ K}$ and 35.9 K respectively.

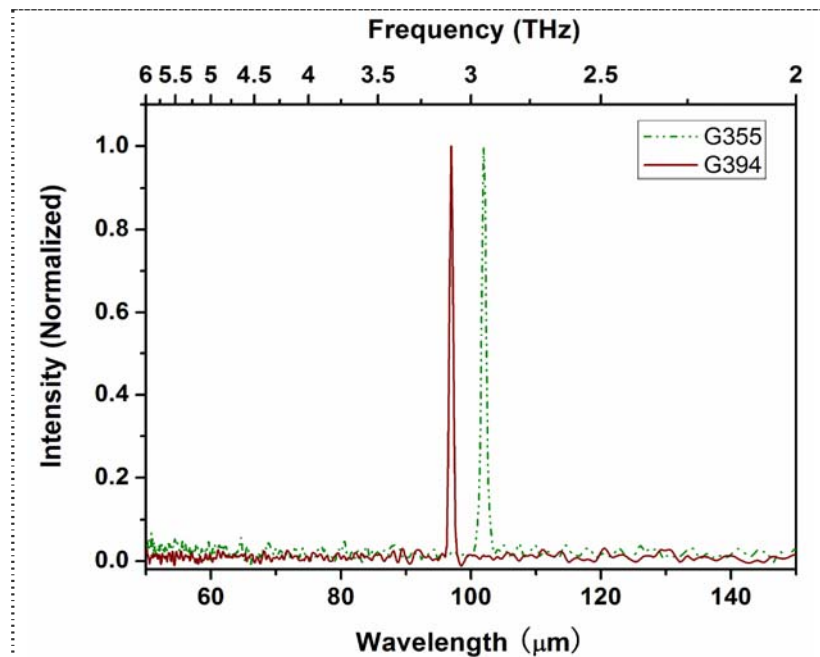


Figure 3. Lasing spectra for G355 and G394 at 10 K under current pulses of 1- μ s duration and 100-kHz frequency at about 1.2 times threshold current.

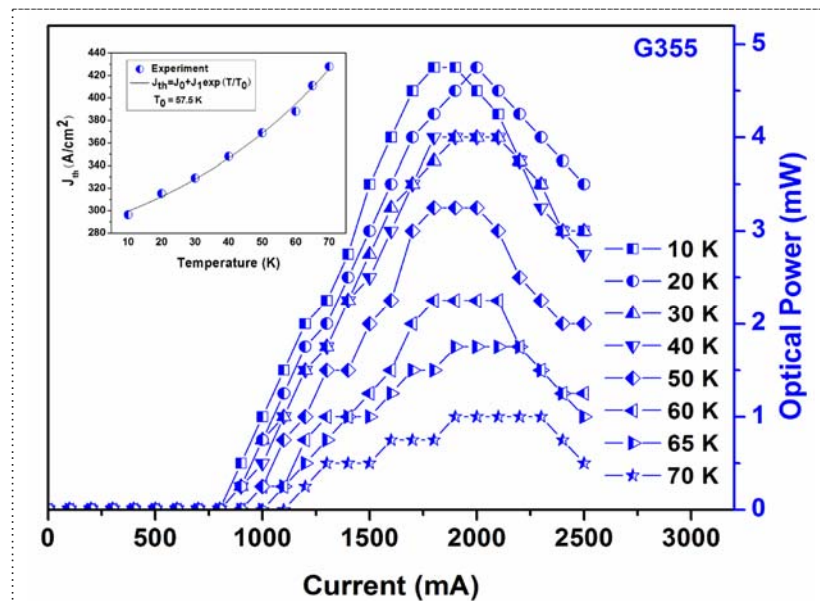


Figure 5. Light power versus current characteristics of G355 at various heat-sink temperatures measured using 1- μ s pulses repeated at 20 kHz. The inset is the variation of threshold current density (J_{th}) with heat-sink temperature (T) along with a fit to the phenomenological relation $J_{th} = J_0 \exp(T/T_0)$.

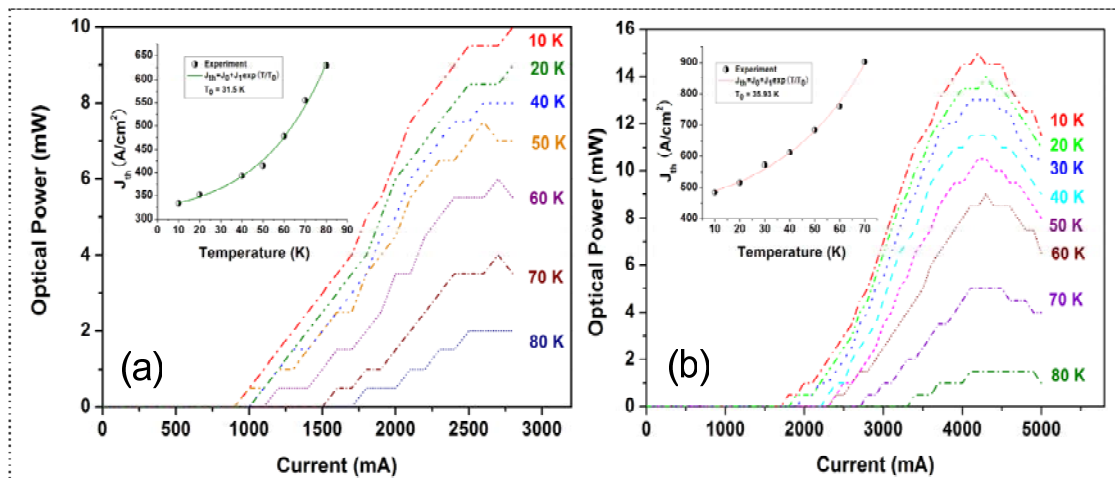


Figure 5. Light power versus current characteristics of G394 at various heat-sink temperatures measured using 1- μ s pulses repeated at 10 kHz for lasers with different length: (a) 1.5-mm-long, (b) 2-mm-long. The relations between J_{th} and T is also included respectively.

4. Conclusions

We have demonstrated THz quantum cascade lasers based on the bound-to-continuum active region and the semi-insulating surface-plasmon waveguide. Due to the growth uncertainties for different wafers, the quantum cascade lasers can operate from 2.94~3.10 THz. For the 3.10 THz quantum cascade laser, lasing is observed up to a heat-sink temperature of 80 K with a peak power of 2 mW. These devices exhibit a potential of higher temperature operation by more well-defined device structure and optimized fabrication processing.

5. References

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