Terahertz frequency quantum cascade lasers: growth and measurement

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Abstract: Results are presented for two GaAs-AlGaAs quantum cascade laser (QCL) structures that emit at frequencies of 2.59 THz and 2.75 THz. Both structures have a nominally identical, bound-to-continuum active region design, and the difference between their emission frequencies is interpreted as resulting from small differences in the gallium and aluminium growth rates, which were measured both before and after laser growth using a pyrometric spectrometry technique. The same technique allows the QCL growth to be monitored real-time, and drifts in growth rates identified.

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I. Introduction

The terahertz (THz) frequency region of the electromagnetic spectrum, spanning the frequency range from approximately 300 GHz – 30 THz, remains relatively unexploited at present, compared with almost all other regions of the spectrum. Yet, there is an enormous potential for the spectral range, with exemplar applications including:

- Screening of pharmaceutical products, with the potential to: determine three-dimensional drug distributions in tablets; distinguish between different polymorphic forms, and; analyze pharmaceutical products through common packaging materials;
- Gas spectroscopy, especially in circumstances where the environment is opaque to radiation from other parts of the electromagnetic spectrum (e.g. in the study of high-pressure combustion, where soot particles will absorb near-infrared radiation, THz frequencies have been shown to be able to access the combustion process successfully);
- The *in vivo* and *in vitro* analysis of human tissues, with ability to diagnose carcinomas in a range of clinical cases;
- The development of security scanners for detection of drugs-of-abuse and explosives.

Given the enormous potential applicability of this part of the spectrum, why have we yet to see widescale take-up of the technology? The answer to this question can be traced back to the technology available. There is still a lack of a cheap, compact and convenient solid-state source that be used in wide-ranging sensor applications. The vast majority of the applications for the THz frequency range have been demonstrated using broadband time-domain systems based on a near-infrared femtosecond pulsed (principally Ti:sapphire) laser technology, and indeed, this technology forms the basis of commercialized THz imaging and spectroscopy systems. However, the high price of near-infrared femtosecond laser systems, and the complexity and large footprint associated with the allied imaging/spectroscopy components, mitigates against the widescale take-up of this technology outside the research laboratory

To make a step-change in the exploitation of THz radiation, a compact, solid-state device is required, analogous to the solid-state diode lasers used today at higher frequencies in CD and DVD players, for example. Yet, the operating wavelength of conventional interband lasers cannot be extended down from near-infrared frequencies to the THz range owing to the lack of suitable semiconductor materials, and the difficulty in maintaining a population inversion. Similarly, the highly efficient electronic microwave devices used, for example, in mobile telephone technology, cannot be easily extended to THz frequencies owing to difficulties with the RC time constants and transit times within the devices.

The semiconductor QCL provides a potential solution. This device comprises a series of two-dimensional quantum wells in which stimulated emission of electrons occurs between quantized subbands. Electrons that have undergone a lasing transition are then fed into the upper lasing level of the next active region, and 'cascade' through the device. The QCL concept dates back to the theoretical proposal[1] of Kazarinov and Suris in 1971, but it was not demonstrated experimentally until 1994 in the mid-infrared,[2] and then ultimately in the THz frequency range[3] in 2002 through the EC consortium *WANTED*. Since this time, there has been a rapid development, with selected highlights including:

- Demonstration of THz QCL operation above liquid nitrogen temperatures;[4]
- Demonstration of continuous-wave operation of a THz QCL;[5,6,7]
- Demonstration of the successive lowering of operating frequency to < 2.5 THz;[8]
- Demonstration of distributed feedback single-mode THz QCLs;[9]
- First measurement of the THz QCL linewidth (<30 kHz);[10]
- Demonstration of heterodyne detection;[10]
- Measurement of enhanced THz emission in a magnetic field;[11]
- Demonstration of the surface-emitting double-metal THz QCL;[12]
- Demonstration of tomographic imaging.[13]

However, THz QCLs still require cryogenic cooling, although there has been rapid progress in increasing the operating temperature from the initial 45 K in 2002 to over 170 K now.[14] On-going programmes continue to push this technology towards an operating temperature accessible by Peltier cooling, and for certain applications, existing cryogen-free cryostats are a convenient and viable alternative.

THz frequency QCLs are extremely challenging structures to grow by techniques such as molecular beam epitaxy (MBE). They require precise calibration of growth rates, and the minimization of flux drifts (to typically <2%) throughout the active region, which usually exceeds 10 μm in thickness and often contains over 1000 separate interfaces. In this article, we demonstrate the successful growth, fabrication and measurement of these sophisticated modulated semiconductor structures. Furthermore, we show how pyrometric spectrometry (kSA BandiT; www.kspace.com/), through a heated viewport, can be used real-time to (a) calibrate GaAs and AlAs growth rates, and (b) monitor the actual growth of QCLs.[15,16]

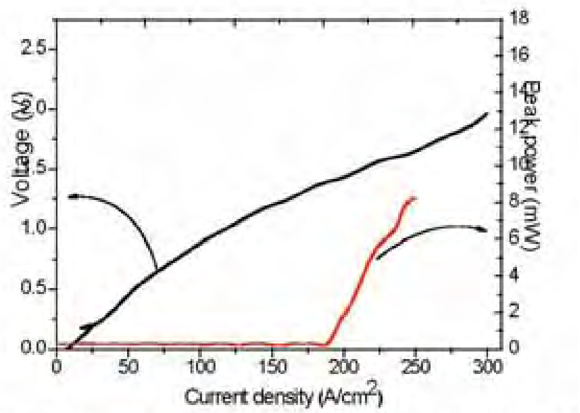

Figure 1 V-L-J characteristics of a 1.85-mm-long, 145-μm-wide QCL (wafer L140), operating at 14 K, obtained with a 25% duty cycle and a 10 kHz pulse repetition rate.

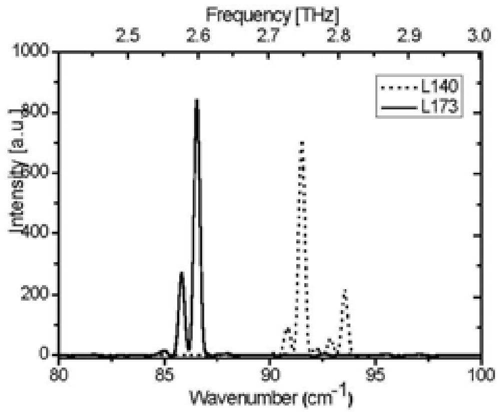

Figure 2 Dotted: Emission spectra of a 1.85-mm-long, 145-μm-wide QCL (wafer L140). Solid: Emission spectra of a 1.75-mm-long, 145-μm-wide QCL (wafer L173). Both lasers were operated at 10 K, with a 25% duty cycle and a 10 kHz pulse repetition rate.

II. Device growth and fabrication

A 2.7 THz QCL (wafer L140) was grown in an Oxford Instruments V-80H MBE system. Based on a bound-tocontinuum active region design and a single plasmon waveguide,[17] the THz laser consists of 90 repeat periods of a GaAs-Al0.15Ga0.85As heterostructure. The active region (11.57 μm thick) is embedded between 80-nm-thick upper (doping density ~5 x 10^{18} cm^{-3}), and 700-nm-thick lower (doping density ~2 x 10^{18} cm^{-3}), n^+ GaAs layers. Following growth, ridge cavities, 145 μm wide and 11.6 μm deep, were defined by optical lithography and wet etched. Upper and lower AuGeNi ohmic contacts were then evaporated/annealed on the upper and lower n^+ GaAs layers in two separate lithography stages. A Ti/Au overlayer was deposited on top of the active region to confine the laser mode from the upper side and create an optical cavity for the laser. The substrate was then thinned to ~250 μm to improve heat dissipation. Processing was completed by cleaving stripes into Fabry-Perot cavities of ~2 mm length, wire bonding and attachment onto copper blocks using indium foil.

Devices were mounted for measurement on the cold finger of a continuous flow cryostat, fitted with polyethylene windows for optical access. Lasers were operated in a pulsed mode for the electrical (voltage (V) vs. current density (J)) and optical (output optical power (L) vs. J) measurements. Fig. 1 shows results obtained when the laser was biased by applying pulses with a 25% duty cycle at a repetition rate of 10 kHz. Emission was collected using a set of parabolic mirrors and detected by a helium-cooled silicon bolometer. A Fourier-transform infra-red (FTIR) spectrometer was used to characterize the emission spectra of the lasers (Fig. 2).

To grow such a QCL structure, calibration of the GaAs and AlAs growth rates was achieved using pyrometric data obtained by growing a thick GaAs layer on AlAs, and vice-versa. In both cases, the intensity oscillations resulting from interference effects in the growing semiconductor layer were monitored as a function of time and wavelength.[15,16] Growth rates were then calculated using

$$G = \frac{1}{T} \times \frac{\lambda}{2\eta} \quad (1)$$

where G is the growth rate, T is the time period of intensity oscillations at a specific wavelength, λ is the wavelength and η is the refractive index. The refractive indices used in this formula were verified using specifically-grown calibration structures, which were also measured in an x-ray diffractometer.

Wafer No.	Al (μm/hr)	Ga (μm/hr)
L140	0.181	0.974
L173	0.184	1.014

Table 1 Aluminium and gallium growth rates calculated from the pyrometric data acquired in specific calibration layers grown immediately after the two THz QCLs.

Table 1 gives the aluminium and gallium growth rates measured immediately after the growth of L140, as well as in a second QCL (L173), grown with a nominally identical active region. It can be seen that the final gallium and aluminium growth rates in L173 are, respectively, 4% and 1.6% higher than in L140. This leads to a reduction in the emission frequency from 2.75 THz in L140 to 2.59 THz in L173, and emphasizes the critical need for careful setting of the gallium and aluminium fluxes, and monitoring of the resulting growth rates.

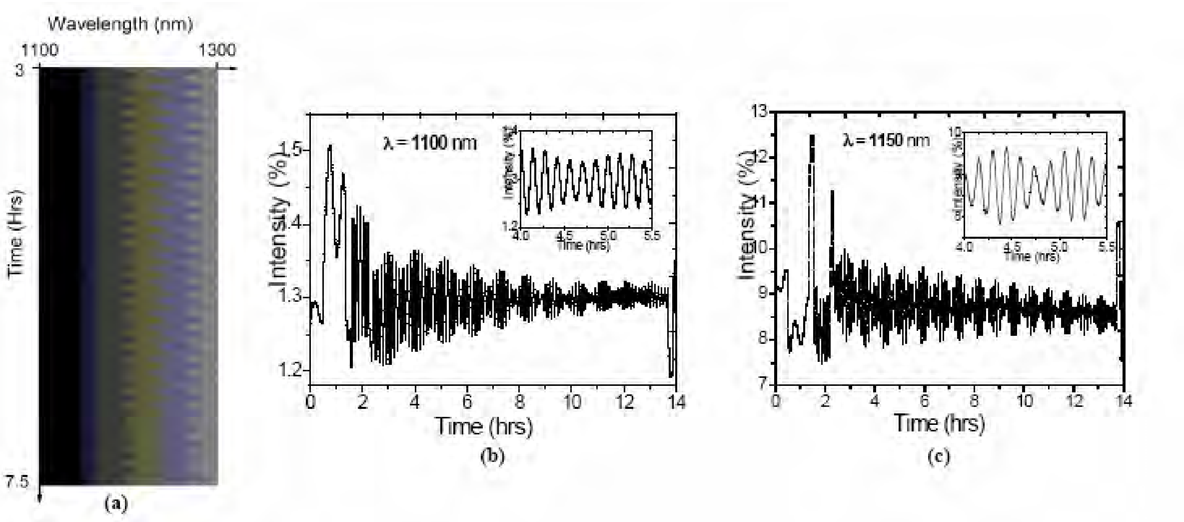

Figure 3 (a) Typical pyrometric data (intensity oscillations) acquired real-time during growth of a THz QCL using the kSA

Bandit spectrometer. Line profiles of the intensity oscillations at specific wavelengths of 1100 nm and 1150 nm are plotted in (b) and (c), respectively.

In addition to using pyrometric spectrometry to calibrate gallium and aluminium growth rates before and after QCL growth, the technique can monitor real time growth of a THz QCL. Figure 3 shows typical pyrometric oscillations for a QCL structure, together with typical line profiles acquired at λ = 1100 nm and 1150 nm. The pyrometric data, in principle, gives extensive information about the precision of the wafer growth, not only acting as an additional calibration during the growth of the QCL itself, but also providing information about flux drifts during a structure's growth.

In summary, the successful growth and fabrication has been demonstrated. Furthermore, a technique has been described for calibrating and monitoring THz QCL growth. This can be applied generally to all THz QCLs, and provides invaluable information for optimizing their performance.

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References

[1.] R F Kazarinov and R A Suris, "Possibility of amplification of electromagneticwaves in a semiconductor with a superlattice". Sov. *Phys. Semiconductors* 5,707–709 (1971).

[2] J Faist *et al.*"Quantum cascade laser" *Science* 264, 553–556 (1994).

[3] R Köhler *et al.*, "Terachertz semiconductor-heterostructure laser", *Nature* 417, 156–159 (2002).

[4] G Scalari *et al.*, "Far-infrared ($\lambda \simeq$ 87 μm) bound-to-continuum quantum-cascade lasers operating up to 90 K "*Applied Physics Letters* 82,3165–3167 (2003).

[5] L Ajili *et al.*, "Continuous-wave operation of far-infrared quantum cascade lasers", *Electronics Letters* 38, 1675–1676 (2002).

[6] R Köhler *et al.*, "High-performance continuous-wave operation of superlattice terahertz quantum-cascade lasers " , *Applied Physics Letters* 82, 1518–1520 (2003).

[7] S Barbieri *et al.*, "Continuous-wave operation of terahertz quantum-cascade lasers", *IEEE Journal of Quantum Electronics* 39, 586–591 (2003).

[8] L Ajili *et al.*, "High power quantum cascade lasers operating at $\lambda \simeq$ 87 and 130 μm ", *Applied Physics Letters* 85,3986–3988 (2004).

[9] L Mahler *et al.* "Single-mode operation of terahertz quantum cascade lasers with distributed feedback resonators ", *Applied Physics Letters* 84, 5446–5448 (2004).

[10] A Barkan *et al.* "Linewidth and tuning characteristics of terahertz quantum cascade lasers", *Optics Letter*s 29, 575–577 (2004).

[11] J Alton *et al.*, "Magnetic field in-plane quantization and tuning of population inversion in a THz superlattice quantum cascade laser ", *Physical Review B* 68, 081303 (2003). (rapid communications)

[12] J A Fan *et al.*, "Surface emitting terahertz quantum cascade laser with a double-metal waveguide", *Optics Express* 14, 11672–11680 (2006).

[13] K L Nguyen *et al.*, "Three-dimensional imaging with a terahertz quantum cascade laser", *Optics Express* 14, 2123–2129 (2006).

[14] M A Belkin *et al.*, "Terahertz quantum cascade lasers with copper metal-metal waveguides operating up to 178 K", *Optics Express* (2008), in the press.

[15] F G Boebel *et al.*, "In-situ film thickness and temperature control of molecular-beam epitaxy growth by pyrometric interferometry", *Journal of Crystal Growth* 150, 54–61 (1995).

[16] F G Boebel *et al.*, "In-situ film thickness measurements by using pyrometric interferometry", Electronics

Manufacturing Technology Symposium (Eleventh IEEE/CHMT International 1991) pp.197−201.

[17] S Barbieri, *et al.*, “2.9 THz quantum cascade lasers operating up to 70 K in continuous wave ”, *Applied Physics Letters* 85, 1674–1676 (2004).