Optimisation of the growth of terahertz quantum cascade lasers

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Introduction

GaAs/AlGaAs quantum cascade lasers (QCLs) are extremely promising, compact, solid state sources for the terahertz (THz) frequency range. They are, however, extremely challenging to grow using molecular beam epitaxy, requiring precise calibration of growth rates, and a minimization of flux drifts (to typically <2%) throughout the active region, which often exceeds 10 µm in thickness and contains >1000 interfaces.

We show that pyrometric spectrometry can be used to (a) calibrate GaAs/AlAs growth rates and (b) monitor the actual growth of QCLs. Using this technique, we demonstrate the successful growth of a range of THz QCLs.

Pyrometric spectrometry

A spectrometer (Fig. 1) can be used to monitor the transmission of a broadband optical beam through a wafer, real-time, during growth. Wavelength-dependant spectra then allow the band gap absorption edge to be measured, and the growth temperature deduced. In parallel, interference effects in the growing layer lead to intensity oscillations (Fig. 2), from which growth rates can be deduced.

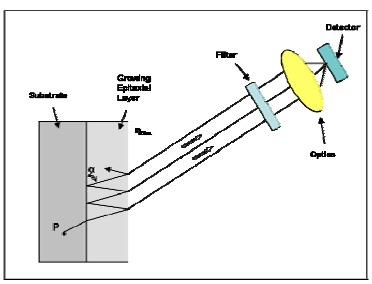

Fig. 1 Diagram illustrating the pyrometric spectrometry technique.

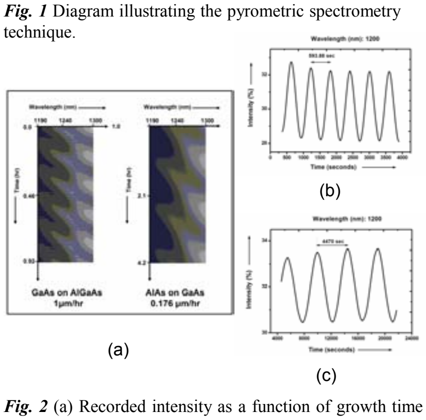

Fig. 2 (a) Recorded intensity as a function of growth time and measurement wavelength; (b) and (c) Intensity oscillations (at a 1200 nm wavelength) observed during growth of GaAs and AlAs respectively.

Growth rates can be calculated from the data shown in Fig. 2, using the formula:

$$G = \frac{1}{T} \times \frac{\lambda}{2\eta},$$

where G = growth rate, T = period, λ = wavelength, and η = refractive index.

Growth of THz QCLs

Two nominally identical wafers (L140 and L173) were grown, based on a 2.7 THz bound-to-continuum QCL design (Fig. 3), using an Oxford Instruments V80H-10 MBE system. The gallium arsenide and aluminium arsenide growth rates were determined immediately after growth using pyrometric spectrometry:

Wafer No.	GaAs (µm/hr)	AlAs (µm/hr)
L140	0.974	0.181
L173	1.014	0.184

The gallium arsenide growth rate was 4% greater in L173, and this manifests itself in a shift in emission wavelength (Fig. 4).

Real-time pyrometric data (Fig. 5) was also obtained during the growth of each THz QCL – this gives an additional calibration of the growth rate, as well as potentially indicating drifts in flux during growth. A Fourier transform of the line profiles from the respective intensity oscillations for L140 and L173 gave oscillation periods of 518.48 s and 491.52 s respectively at λ=1100 nm. Using the refractive index of GaAs, this leads to growths rates of 1.007 and 1.057 µm/hr respectively, demonstrating again the increased growth rate in L173. The slightly higher values of growth rate may reflect the fact that the AlGaAs barriers in the active region have a different refractive index and are grown at 1.18 µm/hour.

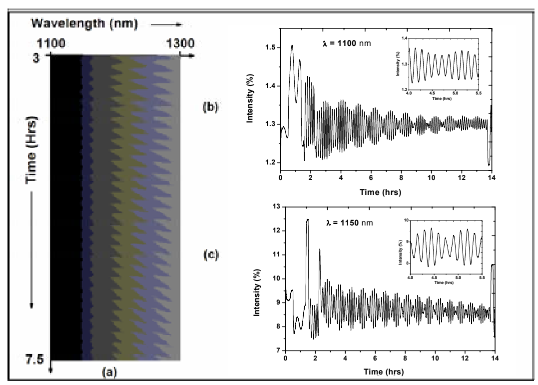

Fig. 5 (a) Typical pyrometric data (intensity oscillations) acquired real-time during growth of a THz QCL, using the kSA Bandit spectrometer. Line profiles of the intensity oscillations at specific wavelengths of 1100 nm and 1150 nm are plotted in (b) and (c), respectively.

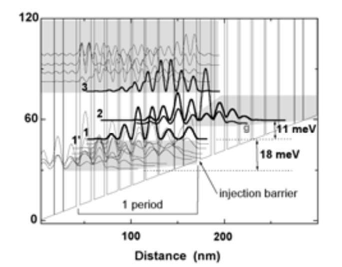

Fig. 3 Bandstructure of a 2.7 THz bound-to-continuum QCL (based on S. Barbieri *et al. Appl. Phys. Lett.* **85**, 164 (2004)).

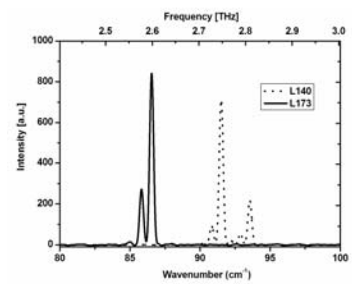

Fig. 4 **Dotted line**: Emission spectra of a 1.85 mm long, 145 µm wide QCL (wafer L140). **Solid line**: Emission spectra of a 1.75 mm long, 145 µm wide QCL (wafer L173). Both lasers were operated at a temperature of 10 K with a 25% duty cycle and a 10 kHz pulse repetition rate.

High temperature operation

Potential applications for THz QCLs are wide-ranging, from security screening and environmental monitoring, through to their use as local oscillators in astronomy. There is, however, a critical need to optimise their performance further to engender widescale uptake of the technology. Fig. 6 shows the performance of an edge emitting THz QCL designed for high-temperature operation. Devices showed a maximum operating temperature of 165 K.

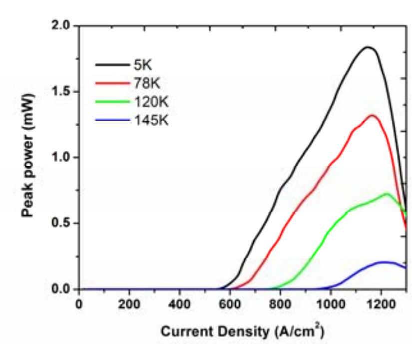

Fig. 6 Temperature dependent L-I curves from an edge-emitting THz QCL (data acquired in a collaboration with J. A. Fan, M. Belkin and F. Capasso at Harvard University). The active region was based on the three well design proposed by H. Luo *et al.* (*Appl. Phys. Lett.* **90**, 041112-3 (2007)).

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