Growth of terahertz quantum cascade lasers

Harvey Beere, Christopher Worrall, Joshua Freeman, Vasilis Apostolopoulos, Jesse Alton, and David Ritchie

***Abstract*—Details of the design, growth, fabrication, and operation of quantum cascade lasers (QCLs) that emit in the terahertz region of the electromagnetic spectrum is presented. Issues associated with the precision, stability, and uniformity of molecular beam epitaxy (MBE) growth needed to achieve optimum device performance is discussed. Robustness studies of the active region of two bound-to-continuum QCL designs, operating at 2.9THz and 2.0THz, against variations in the intended growth rate calibrations are investigated. Initial progress on the transferability of proven THz QCL designs between two different growth systems are presented. Finally, results from approximately 60 QCLs, comprising over 30 active region designs, that emit over a large frequency range from 1.6-4.8THz are reported.**

***Index Terms*—Quantum Cascade Laser, Intersubband, Semiconducting III-V materials, Molecular Beam Epitaxy**

I. INTRODUCTION

Since the first demonstration of a far-infrared quantum cascade laser (QCL) in 2002 [1], QCLs have emerged as an important light source in the terahertz (THz) frequency region of the electromagnetic spectrum. A typical THz QCL active region (AR) design comprises 100-200 repeats of a GaAs/AlGaAs layer sequence that consists of between 12-20 wells and barriers. Consequently, each individual laser structure can contain in excess of 1500 separate layers; with some barriers being as thin as 6Å (~2MLs). Furthermore, with typical deposition growth rates being only of the order ~1MLs^{-1}, the growth time for a typical THz QCL generally exceeds 12 hours. All of the above criteria place enormous constraints on the growth of this type of device structure.

II. PARAMETERS INFLUENCING STRUCTURE GROWTH AND A ROBUSTNESS STUDY OF ACTIVE REGION DESIGNS

Molecular Beam Epitaxy (MBE) is a semiconductor crystal growth technique that facilitates the precise control of the evaporation beam rates (fluxes) and deposition conditions. The unsurpassed level of control over the growth parameters allows extreme dimensional control in the physical thickness, chemical composition, interface abruptness, and doping profiles within the deposited films, making it ideally suited to the growth of THz QCLs.

The operation of the THz laser structure is strongly dependant on the repeatable production of the AR stack throughout the long growth period. This necessitates strict control of, (i) the initial calibration of growth rates, (ii) the stability of the growth fluxes during growth, and (iii) the accuracy of the doping calibration. Figure 1 shows the calculated change in emission frequency (red line) with scaled layer thickness for the 2.9THz bound-to-continuum (BtC) AR design presented in Ref 2; this to a first approximation simulates the variation associated with the gallium growth rate which has been shown to be the dominant source of error [3]. The emission frequency for each scaled AR was obtained, in each instance, by adjusting the electric field to achieve optimum injection efficiency; the anti-crossing between the upper and injector states. This shows that the gallium growth rate must be within ±2% to ensure the laser design emits within ±0.1THz of the intended design frequency (green box). This is consistent with results obtained for other THz QCL AR designs [3].

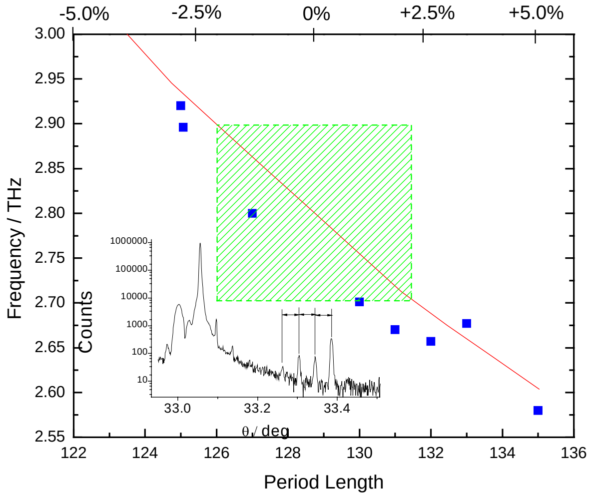

Fig. 1. Calculation of emission frequency as a function of thickness (red line) for the AR of the 2.9THz BtC QCL design in Ref 2. Experimental results from 8THz QCLs with variation in AR thickness (blue squares) as determined by HRXRD. The inset shows a typical HRXRD spectrum.

The simulation however cannot predict if the modified AR designs would actually lase. Consequently a series of 8 THz QCL lasers were grown in which the gallium growth rate was scaled between ±5% the intended AR design thickness. The emission data from the wafers against 'as grown' measured AR thickness is plotted in figure 1 (blue squares). It shows a clear, near linear, trend in good agreement with the simulation; with a frequency span of ~0.35THz. Moreover it confirms that the MBE growth is within the ±2% of the desired thickness for all the structures grown. The above results show the robustness of the bound-to-continuum AR design with respect to unintentional

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Beere, Worrall, Freeman, Apostolopoulos, and Ritchie are associated with the Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, CB3 0HE, UK.

Jesse Alton is associated with TeraView Ltd, Platinum Building, St. John's Innovation Park, Cambridge, CB4 0WS, UK.

Corresponding author Harvey Beere; Telephone: +44 1223 764173; Fax: +44 1223 337271; e-mail: heb1000@ cam.ac.uk).

variations to the original ‘as designed’ structure. A similar robustness study on the 2.0THz BtC AR design [4] will also be reported [5].

III. MINOR ACTIVE REGION DESIGN CHANGES AND THE TRANSFER OF DESIGNS BETWEEN GROWTH CHAMBERS

The ability to reproducibly grow a proven laser design is critical, not only, to the potential manufacturability of these types of laser, but also when introducing minor design changes to the AR. The effect of modifying the injector thickness and doping level on the 2.0THz BtC design [4] will be presented; this highlights the importance of accurate growth for these types of structures.

The systematic transfer of a proven laser structure between different growth chamber platforms is less widely reported. Differences associated with chamber geometries, effusion cell designs, manipulator temperature uniformity, etc, could affect the operation of nominally identical ‘as grown’ QCL devices.

The 2.0THz BtC QCL design [4] was initially grown on a Veeco GENII MBE system, fitted with standard 400g Ga and Al SUMO Veeco effusion cells, using growth conditions described in Ref 3. HRXRD (not shown) showed the AR was 0.8% thinner than the desired design. Figure 2 shows the LIV from a standard 3mm x 250µm ridge laser utilizing a single plasmon waveguide. At 4K, the device lases with a threshold current density of 103Acm^{-2} and peak output power ~23mW at J=139Acm^{-2}. Lasing takes place up to a maximum temperature of 67K. The inset in Fig 2 shows the laser spectrum from the device just operating above threshold in continuous wave at 4K. The device shows single mode emission centered at 2.00THz (8.27meV). The above structure has also been successfully grown, with similar performance, using a Veeco 250g DWL SUMO Ga cell.

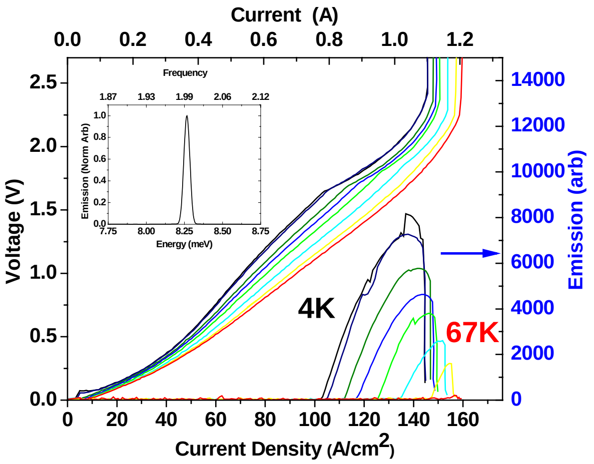

Fig. 2. Voltage vs current and light output vs current density curves for the 2THz ‘Veeco’ QCL (3mm x 250µm ridge). The laser was operated in pulse mode with a 1% duty cycle. Inset, laser spectrum just above threshold

Figure 3 shows the LIV from a standard 3mm x 250µm single plasmon ridge laser for the 2.0THz BtC QCL grown on a VG 80H MBE system; using an EPI 85cc dual filament Ga cell, and a VG 40cc cold lip Al cell. HRXRD (not shown) showed the AR was 0.5% thicker than the desired design. At 4K, the device lases with a threshold current density of 82Acm^{-2} and peak output power ~10mW at J=105Acm^{-2}. Lasing takes place up to a maximum temperature of 57K. The inset in Fig 3 shows the laser spectrum from the device, again single mode emission centered at 1.99THz (8.24meV).

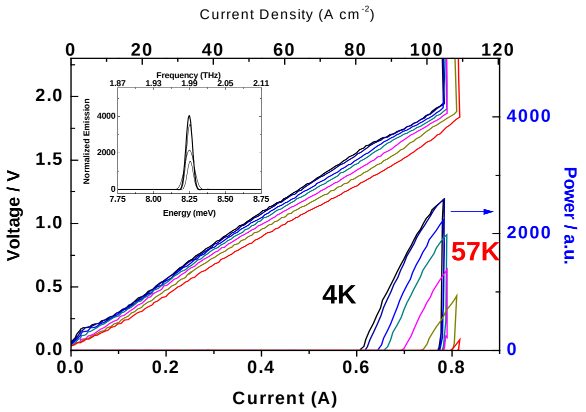

Fig. 3. Voltage vs current and light output vs current density curves for the 2THz ‘VG’ QCL (3mm x 250µm ridge). The laser was operated in pulse mode with a 1% duty cycle. Inset, laser spectrum just above threshold

Clearly, both QCL devices perform to a similar level, with both lasers emitting around the intended 2THz design frequency. The lower operating performance figures for the VG grown structure can be mainly attributed to a lower doping level in the AR injection; both threshold and NDR points are shifted to lower currents [6]. More detailed analysis of the ‘as grown AR’ suggests that the two lasers should emit ~0.1THz apart. A similar trend for the 2.9THz QCL design between the two growth systems is also observed. This highlights slight differences between the two AR designs that cannot be attributed solely to the total AR thickness alone; the cause of which is currently under investigation. However, these results demonstrate the successful transfer of a proven THz QCL design between two different growth systems.

IV. CONCLUSION

We have highlighted the main issues associated with the growth, by solid source MBE, of THz QCLs. A theoretical and experimental investigation into the robustness of two BtC AR designs was presented. In agreement with the theoretical trend, the thinner structures lased at a higher frequency. Moreover, lasing was observed with ARs that were scaled by as much as ±5% in thickness; producing ~0.35THz frequency shift in the 2.9THz AR design. Finally, initial results into the successful transfer of two proven THz QCLs between two different growth systems were reported.

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