Assessment of 1.3-µm InAs QD Edge-Emitting Lasers Grown on Large Area GaAs Substrates

S. Gillgrass[1], C.P. Allford[1], M. Debnath[2], A. Clark[2], P.M. Smowton[1,3]

[1]*School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, UK*
[2]*IQE plc, 484 Gallimore Dairy Rd, Greensboro, NC, 27409, USA*
[3] *Institute for Compound Semiconductors, School of Physics and Astronomy, Cardiff University, Cardiff, UK, CF24 3AA*
Email: GillgrassS@cardiff.ac.uk
Tel: +44 2920 875 478

Keywords: InAs-QDs, EELs, edge-emitting-lasers, sensing, manufacturing, large-area-substrates

Abstract

InAs QD lasers emitting in the 1.3-µm-region have suitable device properties for integration on Silicon either by direct growth or pick-and-place. Assessment of epitaxial wafers for high volume manufacturing is demonstrated here by fabrication of oxide isolated broad-area edge-emitting-lasers and on-wafer characterisation of 150-mm diameter p-doped InAs QD wafers. We report on spatial variations of device data (Power-Current-Voltage-Wavelength) and compare to available epitaxial material data.

INTRODUCTION

InAs quantum dot lasers emitting in the 1.3-µm region have previously been shown to have good temperature stability [1], a broad gain spectrum which can facilitate tuneable or ultra-fast lasers [2] and, importantly for integrated applications, a tolerance to defects which results in good performance when grown directly on silicon [3]. Advanced 3D sensing, data transmission [4] and healthcare applications to name just a few have encouraged the further development of 1.3-µm emitting lasers for high-volume manufacturing in recent years.

This increased demand requires tighter specifications and tolerances, whilst migrating to larger diameter substrates. Rapid assessment and feedback of epitaxial wafers is crucial for maintaining quality and uniformity throughout manufacturing processes and to track any apparent drift in a growth campaign. This has already been shown to be beneficial in VCSEL technologies, through stripped back fabrication and on-wafer measurements [5]. Applying a similar approach to EEL manufacturing would have benefits for a wider range of applications. However, extracting light from EELs on wafer is not trivial, and their performance is influenced by both epitaxy and fabrication.

WAFER PROCESSING

Fabrication is performed at the Institute for Compound Semiconductors cleanroom in Cardiff University, with wafers up to 150 mm diameter patterned on a SÜSS MicroTec MA6 Mask Aligner by contact lithography or using a MicroWriter ML3 Pro direct laser write tool. Commercial scale dry etch, thermal oxidation, and PVD tools are also employed. An Oxford Instruments PlasmaPro 100 Cobra Plasma Etch Tool is used for facet formation by ICP etching with a Cl_2-based gas chemistry.

Deposition of p- and n-type metal contacts is performed using a Kurt J Lesker PVD tool equipped with both thermal and e-beam sources. Capability is being scaled up to process full 200 mm wafers, with state-of-the-art facilities to be housed in the Translational Research Hub, a development which forms part of a £300m Innovation Campus plan at Cardiff University.

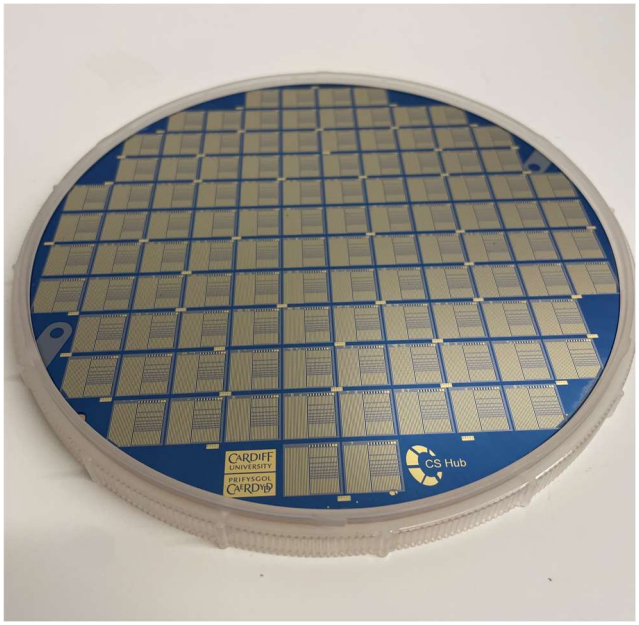

Fig. 1. Oxide isolated broad-area EELs and test structures fabricated over 150 mm GaAs substrate wafer.

MATERIALS AND METHODS

The epitaxial material used in this study is designed for 1.3-µm emission wavelength and grown by MBE, by IQE plc. The design is consistent with direct growth on silicon, but is used here on 150 mm diameter GaAs substrates. It consists of a GaAs/AlGaAs structure with an active region containing 7 layers of p-type modulation doped InAs QDs (Fig. 2).

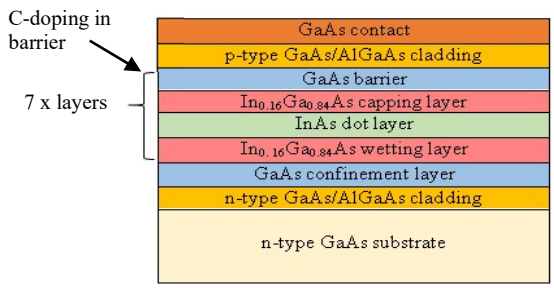

Fig. 2. Epitaxial structure with 7 DWELL layers. Carbon dopant is used for modulation doping layer, situated within GaAs barrier.

We fabricate 50 µm oxide-isolated broad-area EELs over a full 150 mm intact wafer, employing etched facets to enable on-wafer characterisation. An example wafer is shown in Fig. 1. The wafer also incorporates additional structures to evaluate facet efficiency, current spreading, sheet resistance and specific contact resistance.

We report on the device performance and spatial variation, comparing to available growth data, such as peak PL intensity and FWHM, allowing for an understanding of how the growth parameters affect lasing performance at wafer scale. Power-Current-Voltage and wavelength measurements have been performed with threshold current densities of EELs of varying cavity lengths. On-wafer structures are used to measure the current spreading length to allow measured currents to be converted to current densities, using an electrical technique adapted from [6].

Fig. 3. Non-lasing device structures (top), with varying contact width, used to measure current spreading length from electrical V-I measurements.

RESULTS

Measurements of threshold current, in CW operation, across a 150 mm wafer are shown in Fig. 4. It indicates a non-radial variation of performance across the wafer, which correlates to both FWHM and wavelength of PL data, with distinct regions of higher threshold current. However, the variations are not identical. V-I measurements of current spreading structures allow us to estimate mode width without using the near field measurements normally used with singulated devices. Electrical measurements using structures from Fig. 3 show excellent agreement to the standard optical technique allowing mapping across the wafer to account for any changes in the vertical series resistance.

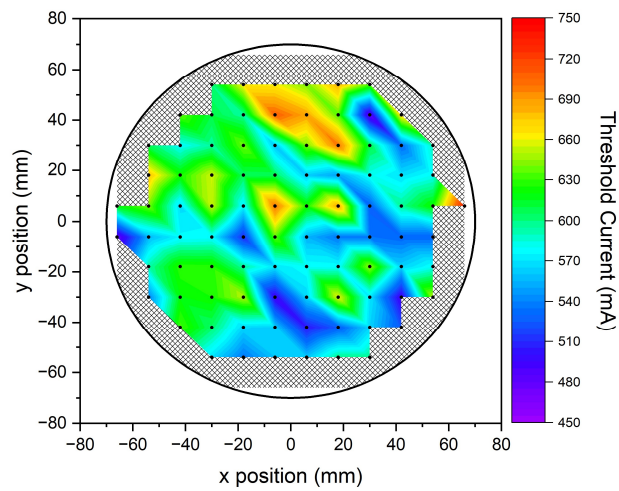

Fig. 4. Heat map of CW threshold current of 2 mm EELs across the 150 mm wafer.

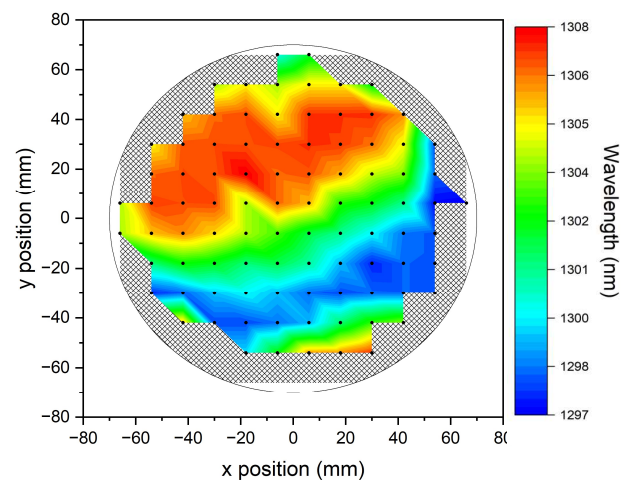

Fig. 5. Heat map of CW lasing wavelength of 2 mm EELs across the 150 mm wafer.

An increase in CW operation emission wavelength of 10.5 nm is observed from bottom left to top right for 2mm long cavity lasers in Fig. 5. This shift from 1297.2 to 1307.7 nm,

measured on wafer, is in agreement once again to the wavelength of PL data, albeit with a red shift due to self-heating. The same wafer has a typical CW threshold current density variation of 0.17 kA/cm^2 across the wafer, based off the threshold current spatial variation seen in Fig. 3.

Roughness introduced by dry etching itself and/or the masking material, affects the laser performance in the same manner. Roughness along the facet, even on the order of λ/10, can cause performance loss [7], and result in elevated device threshold currents when compared to comparable devices with cleaved facets. The P-I characteristic of two identical devices, with different facet types, is shown in Fig. 7. The etched facet device, measured on wafer, has an increased threshold current to the device with cleaved facets, as expected. Assuming a cleaved facet reflectivity of 30%, we can estimate that the facet reflectivity of the etched facet has dropped to ~21%. Understanding this efficiency, is key to ensuring comparable epitaxial assessment.

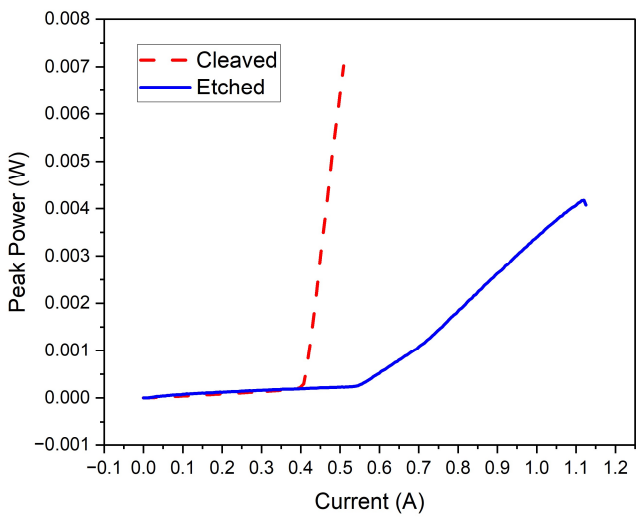

Fig. 7. P-I curves for devices with cleaved (red dash) and etched (blue solid) facets.

CONCLUSIONS

We have described the fabrication and characterisation techniques employed to allow rapid, on-wafer assessment of InAs QD EEL epitaxy. This allows for further understanding of how growth parameters affect laser performance at the wafer scale. Variation in epitaxy leads to distinct variation in threshold current, lasing wavelength and sheet resistance, however, knowledge of etched facet efficiency is imperative in this assessment to disentangle epitaxial and fabrication variations.

ACKNOWLEDGEMENTS

Device fabrication was carried out in the cleanroom of the European Regional Development Fund (ERDF)-funded Institute for Compound Semiconductors (ICS) at Cardiff University.

The EPSRC funded Future Compound Semiconductor Manufacturing Hub: reference EP/P006973/1, the EPSRC funded CS Underpinning Equipment grant: reference EP/P030556/1, and the Strength in Places fund CS Connected, all provided essential resources for this study.

The authors would also like to thank Dr Richard Forrest for his contribution to the experimental setup.

REFERENCES

[1] H. Deng *et al* 2022 *J. Phys. D: Appl. Phys.,* **55** 215105

[2] Y. Wan *et al* 2020 *Laser Photonics Rev.*, 14, 1900348

[3] S. Chen *et al* 2016 *Nature Photonics*, 10. pp. 307-311

[4] M. Liao *et al* 2018 *Photon. Res*., **6**, 1062-1066

[5] J. Baker *et al* 2022 *IEEE Photonics Journal*, 14, 3, pp. 1-10

[6] H. Kim *et al* 2007 *Journ. Quant. Electron,* 43, 8, pp. 625-632

[7] D.A Francis *et al* 1996 Appl. Phys. Lett. 68, 159

ACRONYMS

QD: Quantum Dot
VCSEL: Vertical Cavity Surface Emitting Laser
EEL: Edge-Emitting Laser
PVD: Physical Vapour Deposition
MBE: Molecular Beam Epitaxy
DWELL: Dot-in-well
PL: Photoluminescence
FWHM: Full Width Half Maximum
V-I: Voltage-Current
CW: Continuous Wave
P-I: Power-Current