Characterisation Techniques for On-Wafer Testing of VCSELs in Volume Manufacture

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Abstract – large scale on-wafer mapping of VCSEL performance is a technique widely used as a quality control method in foundry-process manufacturing. Here, techniques are presented for the extraction of information related to epi-layer variation by disentangling effects related to processing.

INTRODUCTION

The recent increase in demand for VCSELs in consumer applications has driven manufacturers to growth on large diameter substrates [1], [2]. For VCSELs, production on 6-inch wafers is still relatively new, whilst 2022 saw the world's first commercially available 8-inch VCSEL wafer [3]. Furthermore, work is being done to improve material uniformity and yield at these large diameter wafers with growth on Germanium substrates [4]–[6].

A key aspect of quality-control in the production of epi-wafers is the on-wafer fabrication and characterisation of VCSEL devices on sacrificial material, which is employed to assess epi uniformity and to track run-to-run drift [7]–[9]. One challenge associated with this analysis is the fact that change in device performance is driven by the effects of both epi-layer variation (doping, composition, layer thickness) and fabrication-dependent variation (mesa size, oxide aperture, contact resistances). In the context of volume wafer production, it is epi-layer non-uniformity and variation that is of concern, hence, any effects resulting from the processing must be characterised and disentangled from device performance. For that purpose, a VCSEL Quick Fabrication (VQF) process was previously developed and its application to large diameter wafers was demonstrated [10]. Here, we present methods for effective characterisation of epi-material quality by decoupling fabrication-driven effects.

METHODOLOGY

Light-current-voltage (LIV) characterisation was performed on VQF devices ranging 26-44 μm mesa diameters and a range of oxide aperture diameters across 6-inch VCSEL wafers. The mask layout is such that a range of apertures are measured at 96 locations, from which heatmaps and contour plots are produced to assess on-wafer variation. Additionally, circular-TLM test structures are processed at each location for mapping contact resistance. The experimental setup consists of an MPI semi-automated probe station equipped with an integrating sphere and calibrated power meter for optical power measurements.

From previous work [10] it was found that oxide aperture non-uniformity contributes greatly to the fab-driven variation, hence it is important to characterise and correct for these effects. For instance, the series resistance of a VCSEL is dependent the on active area of the device, which is determined by the oxide aperture diameter, ϕ. Within an individual 6-inch wafer, ϕ may vary by several microns so mapping the series resistance of a nominally unchanging mesa diameter VCSEL can yield unreliable comparisons between different regions of the wafer. Therefore, a method for obtaining information that is invariant to oxide-aperture non-uniformity is needed.

The VCSEL series resistance can be extracted from the measured current-voltage (IV) characteristic by fitting a Shockley diode equation [11]:

$$V = nV_T \ln\left(\frac{I}{I_{sat}} + 1\right) + R_S I, \tag{1}$$

where the ideality factor, n, the thermal voltage, V_T, and the reverse bias saturation current, I_{sat}, are fitting parameters, and R_S is the series resistance to be extracted. By plotting the resistance as a function of oxide aperture, a fit to the data is extrapolated to infinite active area. In this case, the data is fitted with the following:

$$R_s = \frac{x_1}{A} + \frac{x_2}{{d_m}^2}, \tag{2}$$

where R_s is the measured series resistance, A is the active area, and x_1 and x_2 are fitting parameters with units $\Omega\mu m^2$, and d_m is the mesa diameter. The terms x_1 and x_2 can be expressed as $\rho_{1,2}l_{1,2}$ where ρ is an effective resistivity and l an effective path length for current through a device. The first term represents the contribution of the oxide aperture to device resistance, which is highly dependent on oxide aperture diameter, whilst the second term represents the DBR resistance, which is dependent on the mesa diameter. This is illustrated in Fig. 1. The contributions to total series resistance, $R_{m,t}$, R_{ox}, and $R_{m,b}$ represent the top mirror, oxide layer, and bottom mirror resistances respectively.

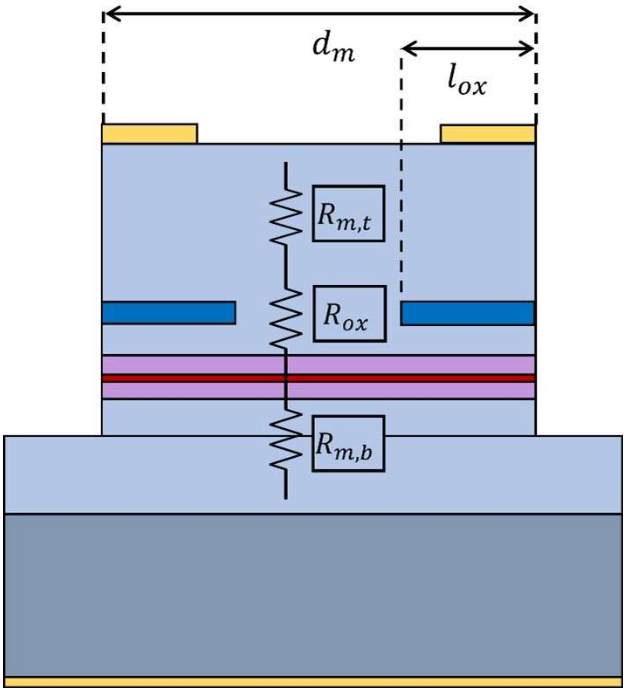

Fig. 1: VCSEL series resistance into separated into contributions due to oxide-aperture and DBR mirrors. In the model applied in this work, the resistance of the top and bottom DBRs are grouped into an effective mirror resistance

In this model, the contribution of the bottom DBR mirror, $R_{m,b}$, and top DBR mirror, $R_{m,t}$, are combined, hence, the second term in equation (2) is an effective total DBR resistance. Fitting (2) to the measured resistances, we are able to map the on-wafer variation of terms x_1 and x_2, which are proportional to the epi-layer resistivity, thus we are able to account for the impact of processing variation and obtain values that are representative of the material properties alone. Furthermore, the VCSEL active area, A, can be expressed in terms of the mesa diameter, d_m, and the oxidation length, l_{ox}, by

$$A = \pi \left(\frac{d_m - 2l_{ox}}{2} \right)^2 . \tag{3}$$

Therefore, also through this analysis, the oxidation length, and hence oxide aperture, can be accurately mapped across a wafer solely from IV measurements. Measurement of TLM structures can also be performed to account for the effects of contact resistance, however, we have found that this contribution is usually negligible.

By applying this treatment to many locations of a wafer, the information gained from VQF characterisation is representative of the properties, in this case the conductivity, of the epitaxial material.

EPI-STRUCTURE

The epi-structure used in this study was designed for 940 nm emission wavelength and was provided by IQE plc, grown at IQE Europe in Cardiff, UK. The structure consists of a MQW region situated in a λ-thick inner cavity sandwiched between an upper p-type AlGaAs DBR and a lower n-type DBR which are made up of AlGaAs layers with AlGaAs/AlAs pairs beneath the active region for reduced thermal impedances. A buried $Al_{0.98}Ga_{0.02}As$ layer was grown in the top DBR for definition of the oxide aperture.

PROCESSING

A VCSEL quick fabrication (VQF) process was applied to whole 6-inch epitaxial wafers to produce oxide-confined devices ranging from ~ 2-16 μm apertures. A VQF device is shown in Fig. 2. Device fabrication was carried out at the Institute for Compound Semiconductors cleanroom at Cardiff University (CU), UK. The cleanroom currently operates at 6-inch processing capability, with capability being scaled up to process 8-inch wafers, at new state-of-the-art facilities to be housed in the Translational Research Hub, CU [10].

The wafers were patterned on a SÜSS MicroTec MA6 Mask Aligner by contact lithography. An Oxford Instruments PlasmaPro 100 Cobra Plasma Etch Tool was used for mesa isolation by ICP etching with a Cl-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.

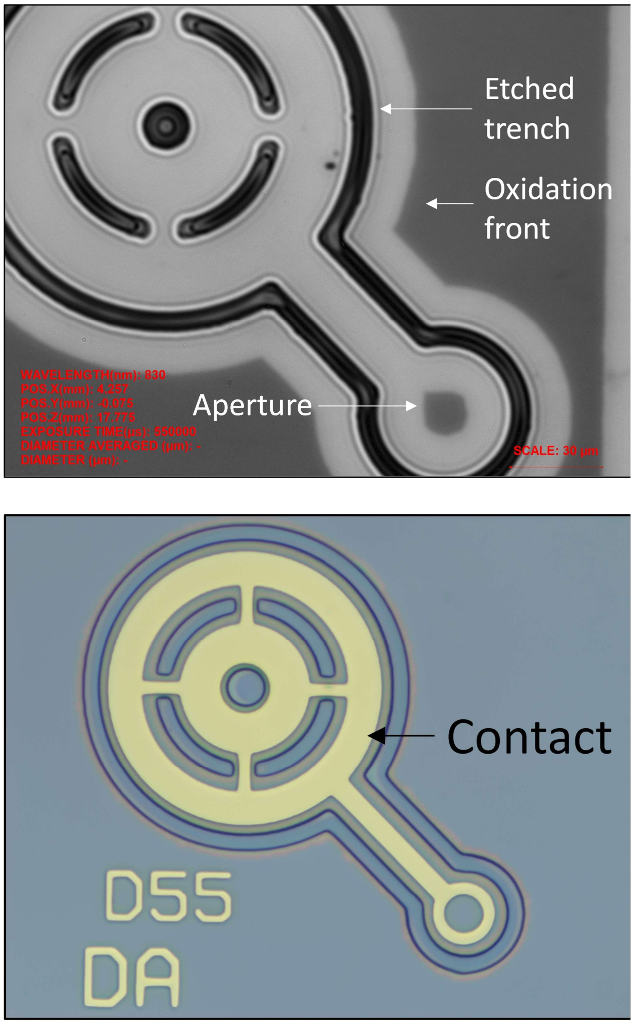

Fig. 2: VCSEL (VQF) quick fabrication device. Top: infrared camera image showing oxidation front and oxide aperture. Bottom: Optical microscope image of fully processed VQF device, from [12].

Results

Continuing with the example of series resistance discussed in the introduction, Fig. 3 shows the measured series resistance as a function of oxide aperture with the fit of equation (1) for the edge of a 6-inch wafer. The separate contributions of the oxide aperture and DBR mirror are also shown in Fig. 3, with the oxidation length as $13.6 \pm 0.5\ \mu$m. The contribution of the oxide aperture to device resistance dominates from small mesas, whilst the contribution of the DBR mirror varies more slowly with mesa diameter and dominates for large devices.

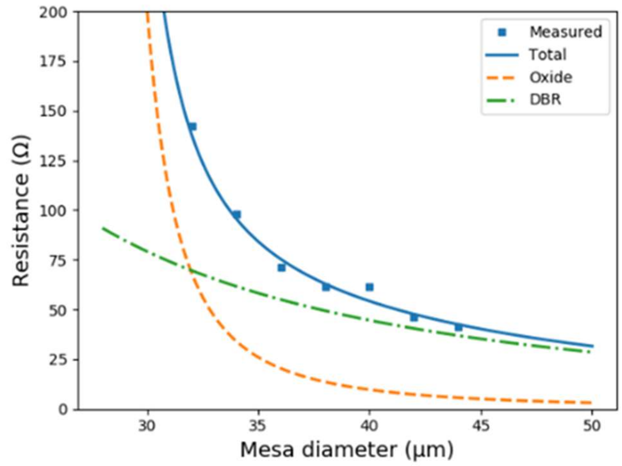

Fig. 3: Measured VCSEL electrical resistance as a function of mesa diameter (blue squares) fit with equation (1) (solid line). The separate contributions due to oxide aperture (dashed line) and top DBR mirror (dash-dot line) are also shown.

Thus, by fitting to the measured VCSEL series resistance as a function of mesa diameter, it is possible to separate out the processing-driven (oxide aperture) and epi-driven (DBR) contributions. The fitting parameters x_1 and x_2 represent effective resistivities and the mapping of these quantities better represent the variation in device performance due to epi-layer variation. Therefore, the method presented here facilitates a reliable assessment of epi-material quality and this has utility for wafer characterisation in-line with a foundry process.

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ACRONYMS

VCSEL – Vertical Cavity Surface Emitting Laser
MQW – Multiple Quantum Well
DBR – Distributed Bragg reflector
AlGaAs – Aluminium Gallium Arsenide
ICP – Inductively Coupled Plasma
PVD – Physical Vapour Deposition
VQF – VCSEL Quick Fabrication
LIV – Light-Current-Voltage
TLM – Transmission Line Measurement