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Improved Thermal Performance of VCSELs on Germanium Substrates

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Abstract—VCSEL thermal resistances are determined from power-current-voltage-wavelength measurements performed on nominally identical epitaxial structures grown on Ge and GaAs substrates. It is shown, for the first time, that an improved thermal performance can be achieved through growth on Ge.

Keywords—VCSEL, GaAs, Ge, thermal resistance

I. INTRODUCTION

In recent years, germanium has been reported to be an ideal drop-in replacement for gallium arsenide as the growth substrate of choice for volume production of AlGaAs-based vertical-cavity surface-emitting lasers (VCSELs) [1]. The key driver behind the work on Ge was the advantageous lattice match with AlAs and (high Al-composition AlGaAs) which circumvents the strain-induced wafer bow suffered with growth on GaAs substrates, although additional benefits include a higher thermal conductivity, higher fracture toughness, defect-free (zero EPD) crystal quality, and the potential to grow on thinner substrates. Since then, we have reported on the benefits of growth on Ge for reducing on-wafer variation of device performance resulting from an improved oxidation uniformity [2], comparable performance of VCSELs grown on 200 mm Ge and GaAs substrates [3], and VCSELs grown on thin Ge substrates [4]. Separately, research has also focussed on the assessment of crystal quality and transition layers between the Ge substrate and AlGaAs epitaxial structure [5], [6], culminating in the successful production of 940 nm VCSELs [7] and demonstration of 25 Gb/s NRZ transmission at elevated temperature [8]. Here, we assess the thermal performance of VCSELs grown on Ge.

II. MATERIALS & METHODS

A. Epitaxial Structure & Device Fabrication

The epitaxial structures used for this study are generic p-i-n layouts designed by IQE plc to operate at 940 nm emission wavelengths. This consists of a MQW active region centred in a λ -thick cavity, sandwiched between p- and n-doped AlGaAs-based DBR mirrors. The bottom DBR mirror contains AlAs layers to improve thermal management. A high Al composition layer is included in the bottom DBR which, after selective oxidation, provides electrical and optical confinement, defining the VCSEL aperture. Nominally identical structures are grown on n-type GaAs and Ge substrates by MOVPE. For structures on Ge, MOVPE-grown buffer layers are included to ensure a smooth transition from Ge to AlGaAs. This is illustrated in the diagram of Fig. 1.

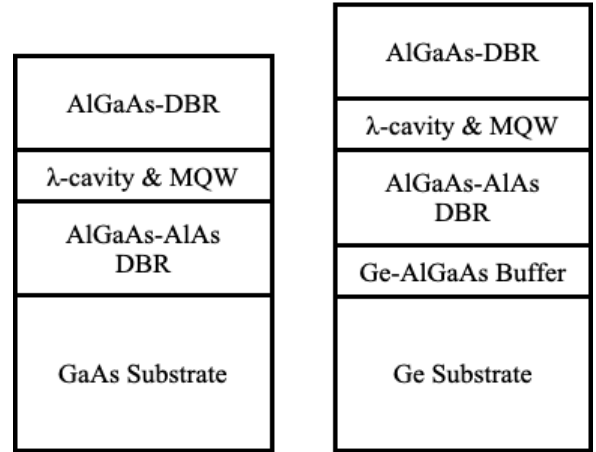


Fig. 1: illustration of epitaxial structures used in this work (not to scale). Structures grown on Ge and GaAs are nominally identical, with the exception of the MOVPE-grown Ge-AlGaAs buffer layer included for growth on Ge.

The devices characterised for this work are Quick VCSEL (QuickSEL) structures, the fabrication process of which is described in [9].

B. Experimental Method

To assess and compare the VCSEL thermal performance, the thermal resistance, R_{Th} , is measured for a range of oxide apertures for devices grown on both Ge and GaAs substrates. We employ the measurement technique described in [10] for the determination of R_{Th} , which we briefly describe here. The thermal resistance can be defined as in equation (1) by the temperature change for a given heat flux:

$$R_{Th} = \Delta T / \Delta P_{diss}, \quad (1)$$

where P_{diss} is the dissipated power:

$$P_{diss} = IV - P_{optical}. \quad (2)$$

Here, IV is the total electrical power equal to the product of the bias current and voltage, and $P_{optical}$ is the total optical power emitted from the VCSEL. The quantity ΔT in equation (1) is not directly measurable, however, the shift of the VCSEL emission wavelength can be used to indirectly measure the device internal temperature. The resulting shift with temperature (in nm/°C) can be used to calibrate the wavelength shift with dissipated power (in nm/mW), the ratio

of which gives the thermal resistance (in °C/mW), as in equation (3):

$$R_{Th} = \Delta T / \Delta P_{diss} = (\Delta \lambda / \Delta T) / (\Delta \lambda / \Delta P_{diss}). \quad (3)$$

By measuring thermal resistance for a range of oxide apertures, the equation $R_{Th} = 1/(2\xi d_{ox})$ can be fitted to the data. This approximates the VCSEL as a disk heat source on a thick substrate, where ξ represents the thermal conductivity of the material separating the heat source from the heat sink [11]. In our case, ξ represents the thermal conductivity of the bottom DBR + substrate (including the transition layers for the Ge substrate devices). Hence, we use the measured thermal resistance to determine values of ξ for the Ge and GaAs substrate structures.

III. RESULTS & DISCUSSION

The VCSEL emission wavelength is extracted from spectral measurement made at a range of bias currents (up to 10 mA). The corresponding dissipated power at each current was determined from the power-current-voltage characteristics. An example of the resulting plots of wavelength versus dissipated power is shown in Fig. 2 (top).

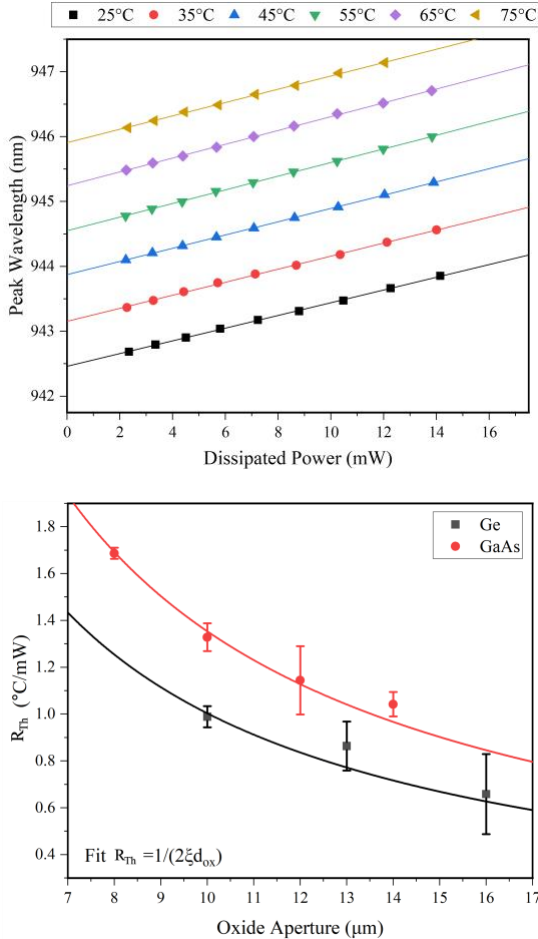


Fig. 2: VCSEL emission wavelength as a function of dissipated power, measured at six temperatures between 25 and 75°C (top); and the resulting thermal resistance values plotted as a function of oxide aperture diameter (bottom).

The thermal resistance is then given by the slope of the curves and this method is performed at six temperatures between 25 and 75°C. The thermal resistance often has a temperature dependent component (as detailed in [10]), however, in this case, we find it the change with temperature to be negligible as seen by the unchanging slopes in Fig. 2 (bottom). Therefore, we consider the thermal resistance at 25°C and its dependence on oxide aperture diameter. The resulting plot is shown in Fig. 2 (bottom). From this fit, we extract thermal conductivities as $\xi_{GaAs} = 0.38$ W/cm°C and $\xi_{Ge} = 0.45$ W/cm°C. These values are both reduced compared to the literature values of thermal conductivity of bulk Ge and GaAs, however, this was expected given the presence of AlGaAs in the DBRs, as well as interface contributions and likely non-ideal thermal contact with the heat sink. Notwithstanding, these results form the first demonstration that the thermal performance of VCSELs can be improved by growth on Ge substrates. These results are non-trivial owing to the need for the Ge-AlGaAs transition layers, and this verifies that the higher thermal conductivity of Ge can be leveraged to improve the thermal transport in VCSELs.

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Device fabrication was carried out at the Institute for Compound Semiconductors (ICS) cleanroom at Cardiff University.

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