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Internal Turn-Off Temperature of Oxide-Confined VCSELs

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***Abstract*—The internal turn-off temperature of oxide-confined vertical-cavity surface-emitting lasers is determined from temperature-dependent power-current measurements. The turn-off temperature and maximum continuous-wave operating temperature are shown to be higher for smaller aperture devices.**

Keywords—VCSEL, internal temperature, oxide aperture

I. INTRODUCTION

The internal temperature of a vertical-cavity surface-emitting laser (VCSEL) subject to continuous-wave (CW) drive current is, in general, not directly measurable. To probe the internal temperature, most often the thermal resistance of a device is determined by measuring the shift in the emission wavelength as a function of both dissipated power and substrate/ambient temperature. From this the average internal temperature of the optical cavity at a given operating point is calculated. With this approach, the propagation of error from the thermal resistance calculation can lead to large uncertainties in the calculated internal temperature. Similarly, the method relies on a low-error determination of the emission wavelength, which requires a high-resolution optical spectrum measurement and the tracking of individual modes. This becomes difficult for multi-modal devices where the mode spacing is small and when considering high drive currents where mode-hopping occurs. The work we present here is motivated by the need for a method to determine the internal temperature of a VCSEL for comparison of different epitaxial designs and device architectures.

The internal temperature at which a VCSEL turns-off, that is, ceases to lase due to thermal effects, has been previously discussed in the literature. Hangauer et al [1] demonstrated that the laser turn-off occurs at a fixed internal temperature. Additionally, Grabherr et al showed the turn-off temperature to be constant, independent of but higher than the heatsink temperature from thermal resistance measurements [2]. The VCSEL turn-off temperature is defined as:

$$T_{off} = T_{hs} + \Delta T_{Joule} = const \qquad (1)$$

where T_{hs} is the heatsink temperature and ΔT_{Joule} is the increase in the internal cavity temperature resulting from Joule heating. When T_{hs} is increased there is a proportional decrease in the magnitude of the internal temperature increase at which the device turns off. This manifests itself in the fact that the CW current at which a VCSEL turns off decreases as the heatsink temperature is increased. Here, we apply a similar method to [1] to extract the average internal cavity temperature at turn-off for oxide-confined VCSELs of varying aperture sizes.

II. MATERIALS & METHODS

A. Epitaxial Structure and Device Fabrication

The epitaxial structures used for this study are generic p-i-n layouts designed and grown by IQE plc. This consists of a MQW active region centred in a λ-thick cavity, sandwiched between p- and n-doped AlGaAs-based DBR mirrors. A high Al composition layer is included in the top DBR which, after selective oxidation, provides electrical and optical confinement, defining the VCSEL aperture. The devices characterised for this work are Quick VCSEL (QuickSEL) structures, the fabrication process of which is described in [3].

B. Experimental Method

The method reported in [1] is used to assess the isothermal performance of VCSELs from CW power-current (P-I) measurements. In this work, we employ part of that method with the focus on determining the internal turn-off temperature. The currents corresponding to threshold (I_{th}), rollover (I_{TR}), and turn-off (I_{off}) (labelled in Fig. 1) are tracked as a function of heatsink temperature. Both I_{TR} and I_{off} decrease with increasing temperature whilst I_{th} increases. The point at which the currents converge represents the maximum CW operating temperature of the VCSEL, $T_{max,CW}$. The plot of I_{off} versus temperature is extrapolated to the x-axis to give the internal temperature at turn-off, that is, the heatsink temperature at which I_{off} tends to zero. For our tests, power-current measurements are performed on-wafer. Electrical contact is made via tungsten tipped probes in four-terminal operation. Optical emission is collected via an integrating sphere with a calibrated power meter. The heatsink temperature is controlled up to 200°C to within ± 0.1°C. We also assess the transverse modal properties of the VCSELs by measuring the far-field (FF) intensity profile using a wide-beam imager and high-resolution CCD camera.

III. RESULTS

The temperature dependence of the threshold, rollover, and turn-off currents for an 8 μm oxide aperture diameter VCSEL is shown in Fig. 1. Labelled in the plot are the maximum CW operating temperature ($T_{max,CW}$) and the average internal cavity temperature at turn-off (T_{off}) which are 172.0 and 187.5 °C, respectively. This procedure is repeated for devices of oxide aperture diameters ranging from ~ 1 to 17 μm.

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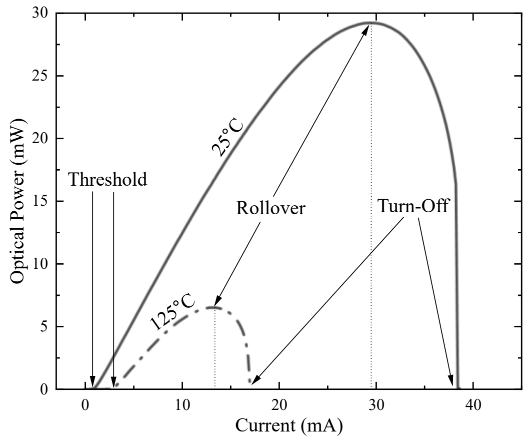

Fig. 1: Power-current curve of an 8 µm oxide aperture diameter VCSEL at 25 and 125 °C with threshold, rollover, and turn-off currents labelled.

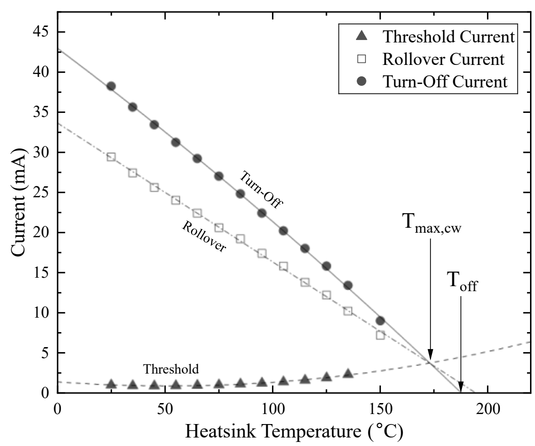

Fig. 2: Temperature dependence of the threshold, rollover, and turn-off currents of an 8 µm oxide aperture diameter VCSEL. Threshold and turn-off plots are fit with a second-order polynomial and rollover is fit with a linear function.

Xun et al previously showed an improved temperature stability for smaller aperture devices, in terms of the peak optical power [4]. Here, we also observe this for the threshold and turn-off currents, that is, d_{th}/dT and dI_{off}/dT is reduced compared to larger aperture devices. Between 25 and 135°C, the threshold current varies by 0.3 mA for a 2 µm device, compared to 8.5 mA for a 14 µm device in the same temperature range. Similarly, the turn-off current drops by 8.0 mA for the 2 µm device, compared to 42.2 mA for the 14 µm device. For a device of aperture ~ 2 µm at 25 °C, turn-off occurs at a current density more than 42x higher than the threshold current density. For a device of ~ 16 µm aperture, turn-off occurs at a current density only 24x higher. Despite higher current densities, smaller aperture devices continue to operate at higher heatsink temperatures than larger devices, as shown in Fig. 3.

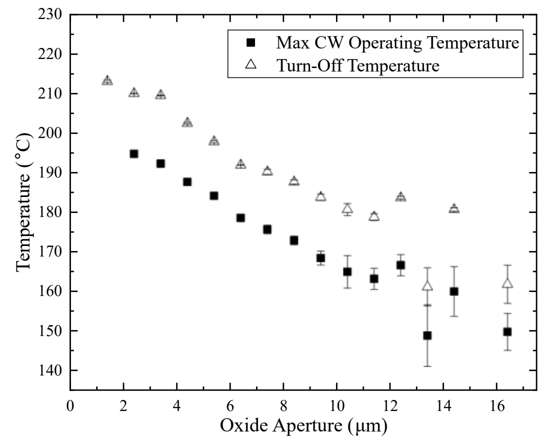

Fig. 3: Experimentally determined internal turn-off temperature and maximum CW operating temperature as a function of oxide aperture diameter.

Furthermore, we also determine that the average internal cavity temperature at turn-off is higher for small apertures at ~ 210°C for a 2 µm aperture device and decreasing to around 160°C for devices above 12 µm aperture. By employing far-field beam imaging, we attribute this effect to the tendency of large aperture devices to high-order mode lasing, which is driven by current crowding at the aperture periphery. This, in conjunction with a thermal-lensing-induced radial temperature profile, means that the optical losses exceed the available gain of the lasing modes in large aperture devices at lower average cavity temperatures than that of small apertures devices.

Acknowledgment

The epitaxial wafers used for this study were designed and grown by IQE plc and device fabrication was carried out at the Institute for Compound Semiconductors (ICS) cleanroom at Cardiff University.

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