PRJ3-1
Invited

Latest progress of high-efficient blue and green VCSELs with curved mirror

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Keywords: light source, VCSEL, laser display, projector, mobile display

ABSTRACT

Highly efficient and uniform GaN-VCSELs with curved mirrors were obtained. The peak WPE and output power were 13.4% and 7.6 mW. This talk also reviews the latest progress of the green VCSELs.

1 Introduction

Vertical-cavity Surface-emitting Lasers (VCSELs) based on gallium nitride (GaN) have attracted the interests of researchers in the field of semiconductor light emitters for decades [1]. VCSELs have a number of advantages, including low power consumption, high frequency operation, arraying capability, and a simplified fabrication process. VCSELs based on arsenide and phosphide-based materials have been employed in a number of applications, including optical communication, laser printers, and sensors. However, GaN-based VCSELs that emit shorter wavelength light such as green, blue, and UV have not been used in practical applications.

Following the publications of the first articles on continuous functioning of GaN-based VCSELs in 2008[2-3], a variety of structures for this device have been proposed. A hybrid distributed Bragg reflector (DBR) system, in which the top side DBR comprises of dielectric materials over a transparent electrode, is one of the most common structural variants. SiO2, Ta2O5, Indium tin oxides, and other oxides are frequently used for the top side DBR. The bottom side, on the other hand, is constructed of nitride-based semiconductor materials in some cases [4].

An AlN/GaN bottom DBR was employed in one example of this type of device [3]. The lattice mismatch between these two materials made this combination challenging. Following this, researchers have developed an AlInN/GaN DBR, in which the composition of AlInN is carefully adjusted to match the lattice constant of GaN [5]. This method allowed for crack-free lamination of these layers, resulting in VCSELs with high wall plug efficiency (WPE) of 8.9% in 2018 [6] and 13.5% in 2021 [7].

Because the bottom DBR, n-spacer, quantum wells, and p-spacer layers can be grown as single crystals using metal-organic chemical-vapor deposition (MOCVD), which is widely used for conventional light emitting devices such as LEDs and edge emitting lasers (EELs), these structures have a simple fabrication process. Multiple institutions, on the other hand, have reported all-dielectric-mirror type VCSELs [2,8-9], in which the mirrors on both sides are made of dielectric materials. There are several ways to make this type of device, but one that combines flat and curved dielectric DBRs yielded the highest WPE of 9.5% in 2018 [10-11], the lowest threshold current (I_{th}) of 0.25 mA in 2019 [12], narrowest emission of 3.9 deg [13] and single longitudinal operation [14].

These reports, which have a high efficiency and a low threshold current, pave the way for effective applications. However, a thorough examination into how the fabrication process affects device uniformity is absent. Lasing yields of up to 80% have been observed for hybrid-DBR VCSELs across a 2-inch wafer, except the outside fringe, and the I_{th} revealed locally arbitrary values rather than smooth drift with wafer positional change [7]. Roughness was seen in AlInN layers generated by MOCVD [15], which was thought to be connected to the semiconductor alloy's intrinsic phase decomposition [15]. On the other hand, there has been very limited discussion about uniformity in the dielectric curved mirror VCSEL. In 2019, only one report demonstrated that the lasing yield was 100% [10]. As a result, the current research looks into device uniformity in terms of current (I) vs. light output power (L)/voltage (V) curves for many devices made from a single test wafer using VCSELs with curved mirrors.

2 Experiment

The current device's construction technique is described elsewhere [16]. The top side DBR and bottom side DBR had 7.5 and 14 pairs, respectively. The

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1* Currently belongs to Leia Inc.

aperture diameter was 3 μm. The cavity length was fixed approximately at 24 μm, while the curved mirrors' radius of curvature was set at 33 μm. Before dividing the wafer containing multiple VCSELs into individual chips, the current-voltage (I-V) and current-light output (I-L) curves of the wafer containing multiple VCSELs were measured with a power source (Keysight B2912A) and photo detector (HAMAMATSU PHOTONICS S1227). The emitters were sliced into separate chips (400 mm x 400 mm) and combined into a φ5.6 TO-can package with a p-up configuration after this measurement. A laser analyzing equipment (ALPHAX LD4200) with a stage temperature of 25 C degree was used to assess the emission spectrum and FFP.

3 Results

Up to 7 mA, the I-V and I-L characteristics of 14 chips were measured. The average threshold current (I_{th}) and optical output power (P_{max}) were 0.64 mA and 4.5 mW, respectively. The standard deviations of I_{th} and P_{max} were estimated to be 0.043 mA and 0.23 mW, respectively, indicating that the curved mirror provided good uniformity. Among these chips, the one with the highest Pmax was mounted on a φ5.6 TO-can and measured. Figure 1 shows the current-WPE (I-WPE) and I-V/L characteristics up to 15 mA, resulting in a maximum WPE and output power of 13.4% and 7.6 mW, respectively, at 5.2 mA and 12.8 mA operating currents. Figure 2 shows FFP above Ith as a single lateral mode with virtually identical full width at half maximum (FWHM) values of 13.3° and 13.5° in the horizontal and vertical axes, respectively. A single longitudinal mode of 442.3 nm can be seen in the emission spectra.

4 Conclusions

We characterized the optical characteristics of several VCSELs with curved mirrors and confirmed that the uniformity with the small standard deviations of I_{th} and P_{max} of 0.043 mA and 0.23 mW under a maximum current of 7 mA at room temperature. The best chip's high efficiency operation of WPE 13.4% at 5.2 mA operational current was also demonstrated. The GaN-based dielectric mirror VCSEL, according to this paper, delivers both high performance and uniformity.

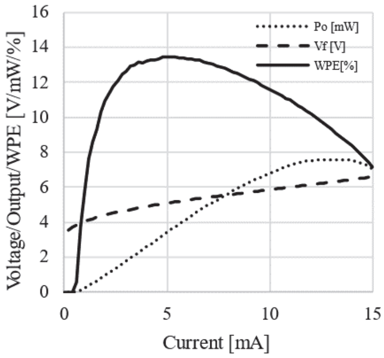

Fig. 1 I-V/L/WPE characteristics of the best chip. These curves are obtained after mounting on a φ5.6 TO-Can.

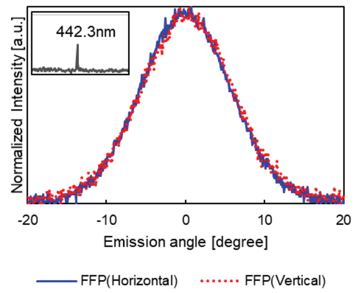

Fig. 2 FFP results in two directions. The inset is obtained emission spectrum

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