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Improved Small-Signal Characteristics of Infrared 850 nm Top-Emitting Vertical-Cavity Lasers

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***Abstract*—**High-speed infrared vertical-cavity surface-emitting laser diodes (VCSELs) with Cu-plated heat sinks were fabricated and tested. VCSELs with 10 μm aperture diameter and 4 μm of electroplated copper demonstrated a -3dB modulation bandwidth (f_{-3dB}) of 14 GHz and a resonance frequency (f_R) of 9.5 GHz at a bias current density (J_{bias}) of only 4.3 kA/cm^2, which corresponds to an improved $f_{-3dB}{}^2/J_{bias}$ ratio of 44 GHz^2/kA/cm^2. At higher and lower bias current densities, the $f_{-3dB}{}^2/J_{bias}$ ratio decreased to about 30 GHz^2/kA/cm^2 and 18 GHz^2/kA/cm^2, respectively. Examination of the analogue modulation response demonstrated that the presented VCSELs displayed a steady f_{-3dB}/f_R ratio of 1.41±10% over the whole range of the bias current ($1.3I_{th}$ to $6.2I_{th}$). The devices also demonstrated a maximum modulation bandwidth ($f_{-3dB\ max}$) of more than 16 GHz at a bias current less than the industrial bias current standard for reliability by 25%.

***Keywords*—**Current density, High-speed VCSELs, Modulation bandwidth, Small-Signal Characteristics, Thermal impedance, Vertical-cavity surface-emitting lasers.

I. Introduction

THE utilization of optical interconnects technology is considered to substitute the current copper interconnects technology due to the demand for high-speed data transfer rates and routing. VCSELs have been broadly considered as the light source of choice in many areas such as high-speed local area networks, printing, engraving, and displays. Such an interest in VCSELs arises due to their several advantages such as planar fabrication of two-dimensional arrays, reduced power consumption, easy integration [1], [2]. Presently, VCSEL-based interconnects utilizing VCSELs emitting at 850 nm wavelength and operating at data transfer rates up to14 Gbit/s dominate commercial data communication systems.

The VCSEL -3dB modulation bandwidth is typically affected and ultimately limited by extrinsic effects such as thermal effects and parasitic circuit effects [3], [4]. Hence, introducing VCSELs with new structure and/or fabrication methods to limit these extrinsic factors is essential to fabricate reliable VCSELs with improved performance for higher data transfer rates. Many techniques for reducing the modulation extrinsic limiting factors, which include parasitic capacitances and resistances reduction, have been previously reported [4]-[8]. Device reported in [9] required bias current densities of 20 kA/cm^2 to exhibit modulation bandwidths of 23 GHz. On the other hand, at their current densities, the VCSEL reliability is reduced since the VCSEL failure rate is directly proportional to the bias current density squared [10].

The presented work reports on the fabrication and performance of oxide-confined, metal-plated, dielectric (polyimide)-planarized, *n*-side up VCSELs with 850-nm wavelength. The presented devices utilized plated copper at a metal heat sink for internal junction temperature reduction and epitaxial structure on a *p*-type substrate for reduced VCSEL resistances. Planarization and parasitic pad capacitance reduction was achieved using HD-8000 Microsystems^{TM} photosensitive polyimide [2]. Reported devices demonstrated a -3dB modulation bandwidth of 14 GHz and a resonance frequency of 9.5 GHz at a bias current density of only 4.3 kA/cm^2, which corresponds to a maximum $f_{-3dB}{}^2/J_{bias}$ ratio of 44GHz^2/kA/cm^2. At higher and lower J_{bias} the $f_{-3dB}{}^2/J_{bias}$ ratio decreased to 29.7 GHz^2/kA/cm^2 and 18.1 GHz^2/kA/cm^2, respectively. Examination of the analogue modulation response demonstrated that the presented VCSELs displayed a steady f_{-3dB}/f_R ratio of 1.41±10% over the whole range of the bias current. The devices also demonstrated a maximum modulation bandwidth ($f_{-3dB\ max}$) of 16.4 GHz at a bias current of only 6 mA, which is less than the industrial bias current standard for reliability by 25% [11], [12].

II. VCSEL Fabrication Summary

Several processing steps were carried out using a sequence of several photomasks. VCSEL fabrication started with the formation of about 5 μm height mesas with 30 μm diameters using a load-locked Trion Minilock II ICP dry-etching system equipped with an optical interferometric monitor. Next, the sample was wet-oxidized at elevated temperatures in a steamy environment using a CARBOLITE tube furnace with electrical heating elements resulting in an oxide aperture diameter of 10 μm. Metal systems were deposited to form the top n-type and bottom p-type metal contacts. To get the overhanging resist profile necessary for successful photoresist lift off, LOR-10B resist, which is based on the PMGI (polydimethylglutarimide) platform, was used.

To electrically insulate the active region from the plated copper heat sinks, a layer of silicon nitride was deposited and partially etched in the Technics Micro-RIE System using tetrafluoromethane and oxygen to electrically insulate the mesa sidewall from later metallic. For planarization, positive tone photo-definable polyimide with a built-in adhesion

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promoter was used. Finally, electroplated metal interconnects and bonding pads (probing pads) that allow for electrical connection to the VCSEL were applied, where a 4-µm thick copper probing pads/heat sinks where plated using a four-point configuration setup [2], [13]. Fig. 1 illustrates a schematic cross-sectional view of the fabricated VCSEL ready for testing.

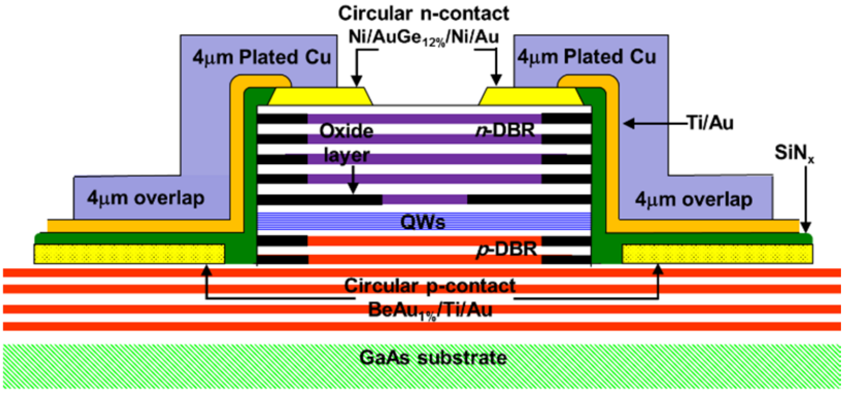

Fig. 1 A schematic cross-sectional view (not to scale) of the fabricated 850-nm VCSEL ready for testing

III. Results and Discussion

The DC and AC performances of the fabricated oxide-confined, metal-plated, polyimide-planarized, *n*-side up VCSELs with mesa and oxide aperture diameters of 30 µm and 10 µm, respectively, were measured at room temperature [14]. The continuous-wave (CW) output optical power, voltage, and -3dB modulation bandwidth as a function of the bias current were measured using a probe station equipped with a vacuum chuck, probing tips/microprobe, a CCD camera, a bias tee, a graded index fiber, a high-speed photodiode, and a low noise amplifier. A four-channel semiconductor parameter analyzer and a Keithley Source Meter were used to measure the electrical characteristics of the reported devices. For optical characteristics, a vector network analyzer and an optical spectrum analyzer were utilized.

The measured CW output optical power demonstrated a maximum output optical power of about 0.9 mW when biased at ~13.2 mA. The reduced output optical power is believed to be due to the highly reflecting 25 top n-DBR pairs. The electrical power dissipated in the presented devices reached about 42 mW to achieve the maximum output optical power. The VCSELs' thermal impedance was estimated as described in [14] of about 1.01 ºC/mW. Electroplating the reported VCSELs with copper reduced the measured thermal impedance by approximately 62% compared to the VCSELs $Z_{thermal}$ reported previously by the author and collaborators in [15], [16].

The small signal modulation response of the fabricated devices was measured at different bias currents, where measurements were terminated when the measured -3 dB modulation bandwidth saturates. Fig. 2 demonstrates the -3 dB modulation bandwidth and resonance frequency as a function of the bias current at room temperature, where the reported devices demonstrate a maximum -3 dB modulation bandwidth of 16.4 GHz and a resonance frequency of 11.7 GHz at a bias current of about $5.4I_{th}$ (6 mA). The 6 mA current corresponds to a bias current density of 7.5 kA/cm^2, which is about 36% less than that reported in [17] to exhibit a maximum -3 dB modulation bandwidth of only 15.2 GHz. Compared to the 10 kA/cm^2 bias current density required for current very reliable 10 Gb/s VCSELs, the presented VCSELs required current densities less than the 10 kA/cm^2 by 25% (7.5 kA/cm^2). Thus, device reliability should be improved since elevated bias current densities cause an increase in junction internal temperature and speed-up device failure. VCSELs reported in [12], [18] required bias current densities of 19.8 kA/cm^2 to exhibit modulation bandwidths of 16 GHz. Hence, the VCSEL reliability is significantly reduced at such a high bias current density. Such a conclusion is supported by the results reported in [2], [12], [19], [20], where reliability tests of 850-nm VCSELs demonstrated that 50% of the devices failed after ~900 and ~350h of operation when biased at 7.5 and 9 mA, respectively. Fig. 3 illustrates the f_{-3dB}^2/J_{bias} ratio as a function of J_{bias}, where a maximum f_{-3dB}^2/J_{bias} ratio of 44 GHz^2/kA/cm^2 is achieved at J_{bias} of only 4.5 kA/cm^2. At higher and lower bias current densities the f_{-3dB}^2/J_{bias} ratio decreased to 29.7 and 18.1 GHz^2/kA/cm^2, respectively. The reported maximum -3 dB modulation bandwidth of 16.4 GHz corresponded to an improved f_{-3dB}^2/J_{bias} ratio of 35.6 GHz^2/kA/cm^2 compared to the results reported in [21], [22] where polyimide wrapped 7 µm oxide aperture 850 nm devices exhibited f_{-dB}^2/J_b ratio of only 24.7 GHz^2/kA/cm^2.

To further investigate the small signal response, the -3dB modulation bandwidth to resonance frequency ratio (f_{-3dB}/f_R) as a function of the bias current density was investigated. Such a ratio is of interest as it indicates the level of damping the presented VCSELs' suffer might from, where a theoretical value of f_{-3dB}/f_R ratio of ~1.55 has been reported [15]. Thus, the smaller f_{-3dB}/f_R the higher the damping. To clarify this, Fig. 4 illustrates measured -3 dB modulation bandwidth to resonance frequency f_{-3dB}/f_R ratio as a function of the bias current density above threshold. From Fig. 4, it can be seen that the presented devices demonstrated a steady f_{-3dB}/f_R ratio of 1.41±10% over the whole bias current range used ($1.3I_{th}$ to

$6.2I_{th}$).

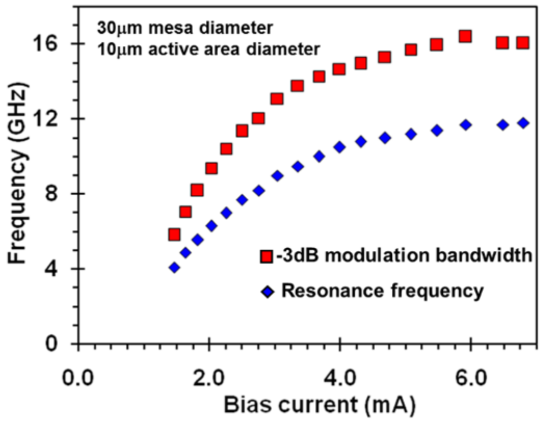

Fig. 2 Measured -3 dB modulation frequency and resonance frequency as a function of the bias current above threshold

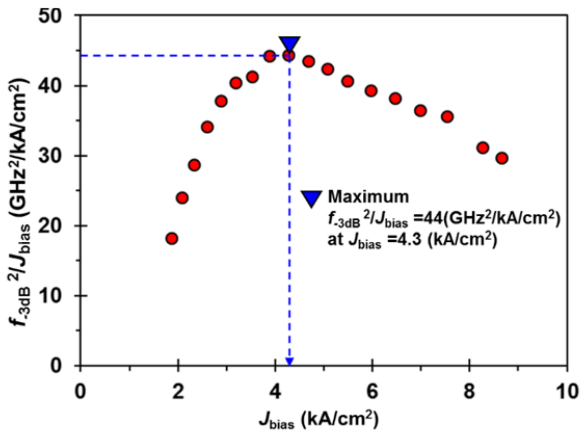

Fig. 3 Measured -3 dB modulation bandwidth squared over bias current density ratio

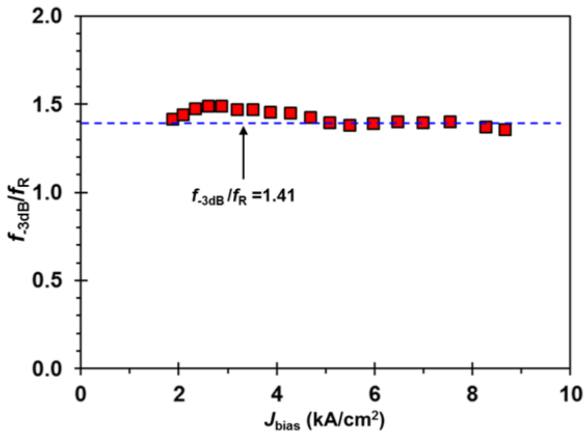

Fig. 4 Measured -3 dB modulation bandwidth to resonance frequency f_{-3dB}/f_R as ratio a function of the bias current density above threshold

IV. Conclusion

In this paper, top-emitting, oxide-confined, Cu-plated, *n*-side up VCSELs emitting at 850-nm were fabricated and characterized. VCSELs with 30 μm mesa diameter, 10 μm oxide aperture, and 4 μm of metal-plated heat sink exhibited a maximum -3 dB frequency modulation bandwidth of 16.4 GHz and a resonance frequency of 11.7 GHz at a bias current density of 7.5 kA/cm^2, which is 25% less than the industrial benchmark current density for reliability. Reducing the bias current density by 42% (4.3 kA/cm^2) reduced the maximum achievable bandwidth by 14% (14 GHz), but increased the maximum achievable $f_{-3dB}{}^2/J_{bias}$ ratio by 22% (44 GHz^2/kA/cm^2).

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