High-speed characteristics of large-area single-transverse-mode vertical-cavity surface-emitting lasers

T.-H. Hsueh, H.-C. Kuo, F.-I. Lai, L.-H. Laih and S.C. Wang

The single transverse mode operation of VCSELs with low threshold current (I_{th}) of 1.5 mA, slope efficiencies about 0.35 W/A, high optical output power of 3.8 mW and speed performance of 10 Gbit/s is reported. The laser has continuous-wave operation and employs oxygen implantation, MOCVD regrowth and selective oxidation on semi-insulating GaAs substrate.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) have attracted much attention in recent years because of their potential for high-volume low-cost manufacturability and packaging, low drive currents, simple two-dimensional (2D) array fabrication and use as a light source for fibre-optic data communication links [1]. High-power single-mode operation is desirable for a number of applications, including high-speed laser printing, optical storage and long-wavelength telecommunications. There are two different techniques for fabricating single-mode VCSELs. One is to make the device small enough to support only the fundamental mode, for which the best results have been achieved using oxide-confined VCSELs [2] with optimised position of the oxide layer [3]. For oxide-confined VCSELs, the emission area needs to be reduced to 3 µm diameter to have stable aperture single-mode operation. However, small aperture oxide-confined VCSELs are more sensitive to process variation. In addition, lifetimes of smaller aperture oxide VCSELs decrease proportionally with area even when the reduced operating currents are taken into account [4].

The other technique used to fabricate fundamental mode VCSELs with larger emission areas include increasing the higher-order mode loss in a larger multimode by surface-relief etching [5, 6] and extending the optical cavity [7]. Young *et al.* have proposed a hybrid implant/oxide VCSEL to obtain single-mode operation based on 'cold-cavity' considerations. The basic idea is to increase the optical losses of higher-order modes [8]. However, the threshold current (I_{th}) of this VCSEL is on the high side: ~5.8 mA. In this Letter, we report the realisation of single-mode operation of VCSELs with low I_{th} and high-power by employing oxygen (O^+) implantation, MOCVD regrowth and selective oxidation on semi-insulating GaAs substrate. Two types of apertures in this device have been designed to decouple effects of the current confinement from those of the optical confinement. One is the oxygen-implanted aperture (8 µm diameter) for confinement of the current flow. The other is the oxide aperture (10 µm diameter) for optical confinement.

Experiment: The schematic diagram of the VCSEL structure is shown in Fig. 1. The epitaxial structure was grown by metal organic chemical vapour deposition (MOCVD) on a semi-insulating GaAs (100) 6° toward (111A) substrate. Prior to O^+ implantation, the wafer structure consists of a n^+-GaAs (Si doped) buffer layer and a 39 pair n-type (Si doped) $Al_{0.19}Ga_{0.81}As/Al_{0.9}Ga_{0.1}As$ bottom Bragg mirror, $Al_{0.26}Ga_{0.74}As/GaAs$ five-quantum-well active region in a one-wavelength cavity for 850 nm emission, and two pairs of p-type (C doped) $Al_{0.19}Ga_{0.81}As/Al_{0.9}Ga_{0.1}$ top Bragg mirror. A 50 Å GaAs cap layer was grown and the location was designed at the null position of the optical field to avoid optical absorption. In addition the GaAs layer was used to prevent oxidation on the surface before regrowth. The O^+ implantation was conducted at 120 keV with a dosage of $\sim 2 \times 10^{14}$ to define current apertures of 8 µm in diameter. Regrowth of a 24 pair top Bragg mirror with a 30 nm $Al_{0.98}Ga_{0.02}As$ layer for wet oxidation located at the third null node position then started after activation by 400°C thermal annealing. The activation process gave the implanted layer good insulation. The implanted position in our device using the regrowth technique is deeper than for other conventionally implanted VCSELs. The surface relief pattern of 20 µm in diameter was then transferred onto the surface of the top mirror to n-DBR layers below the QWs using chemically assisted RIE. Gases used in the ion source and flowing over the sample were Cl_2 and BCl_3, respectively. Then the samples are selectively oxidised to form the circular optical apertures of 10 µm diameter. Further processing of the VCSELs involved mesa wet etching, selectively wet oxidation, deposition of metallic contacts and planarisation using a polymide bridge.

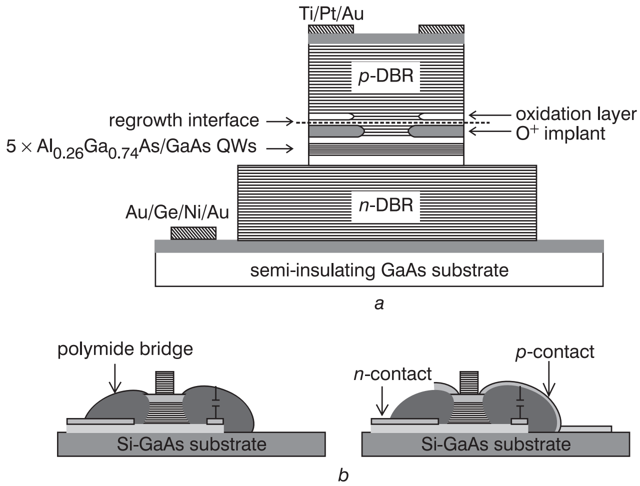


Fig. 1 *Schematic diagram of structure*

a Schematic structure of single mode VCSEL. O^+ implant aperture is 8 µm in diameter and oxidation apertures have 10 µm diameter
b Device process flowchart

Results: Fig. 2 shows CW current, voltage, output power (L–I–V) and spectral characteristics (inset) of the fabricated VCSELs. The VCSEL exhibits a low threshold current of 1.5 mA with threshold voltage of 1.7 V and slope efficiencies ~0.35 W/A. The laser emits near 3.8 mW peak power at a 12.3 mA drive current. The spectral response and the near-field pattern (inset in Fig. 2) operating at 10 mA and 5 mA, respectively, confirm that only the fundamental mode is present over the full operation range. More than 90% series resistance of the VCSELs is within 60–65 Ω, indicating a good regrowth interface and the advantages of low resistance of larger aperture VCSELs. Additionally, the rollover current is around 12 mA, which is also larger than for small size aperture VCSELs, which should lead to better reliability [2]. To measure the high-speed VCSEL under large signal modulation, microwave and lightwave probes was used in conjunction with a 10 Gbit/s pattern generator and a 12 GHz photo-receiver. The eye diagrams were taken for back-to-back (BTB) transmission on our VCSELs. The measurements on our VCSELs were conducted on an SMA sub-mount operating at 10 Gbit/s with 5 mA bias current and 6 dB extinction ratio (Fig. 3*a*). The wide open eye pattern indicates good performance of the single-mode VCSEL. The rise time (T_r) and fall time (T_f) are estimated to be 28 ps and 38 ps, respectively, with jitter (peak–peak) = 14 ps. For comparison, the conventional oxide multiple-mode VCSEL with 8 µm aperture diameter operating at 10 Gbit/s with 5 mA bias current shows more noisy eye pattern with jitter = 17 ps (see Fig. 3*b*).

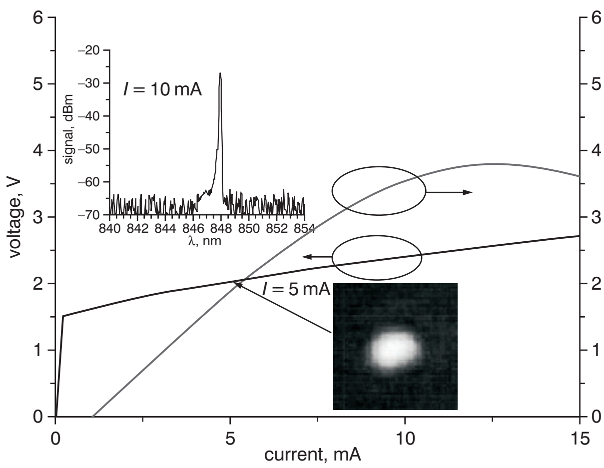
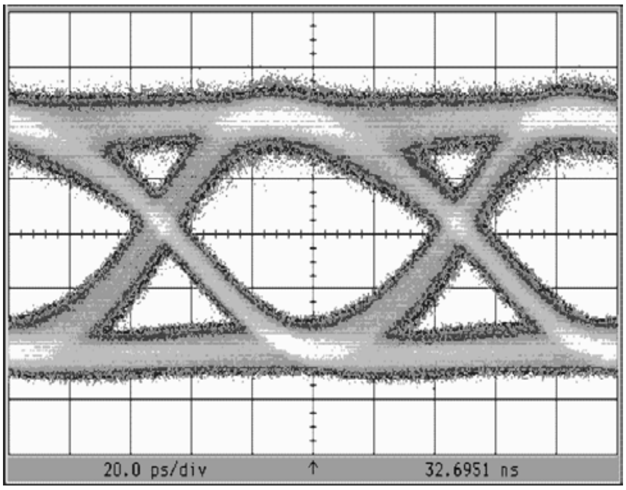
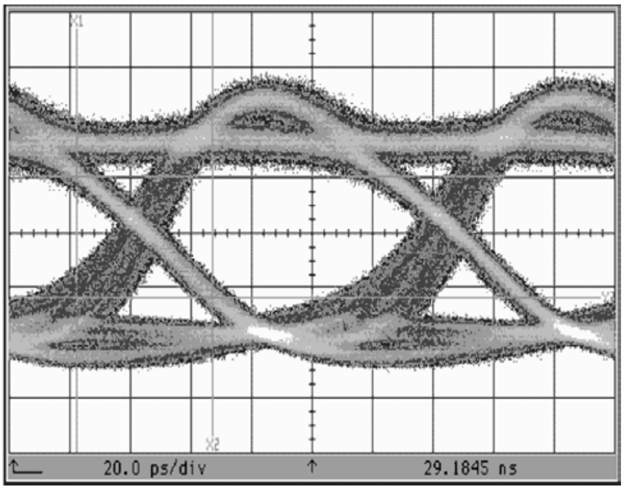


Fig. 2 *L–I–V curve for single-mode VCSEL with 8 µm diameter O^+ implant aperture and 10 µm diameter oxide index guide*



a



b

Fig. 3 *Characteristic eye diagram*

a Single mode
b Multiple-mode
VCSELs transmitting 10 Gbit/s with 5 mA bias and 6 dB extinction ratio

Conclusions: A high-power (>3.8 mW) and high-speed performance (10 Gbit/s operation) large-area single mode VCSEL is reported, with low threshold, employing oxygen implantation, MOCVD regrowth and selective oxidation. The concept should be applicable to long wavelength VCSELs.

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