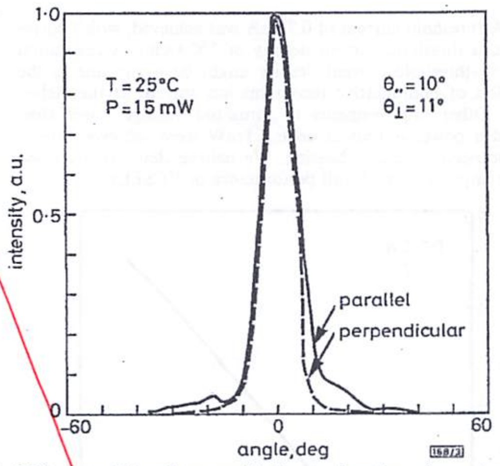
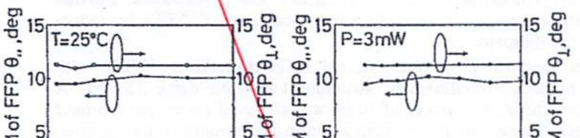


Fig. 3 *FFPs parallel and perpendicular to junction plane at output power of 15mW*

The $\theta_{\parallel}$ and $\theta_{\perp}$ are 10 and 11°, respectively. The aspect ratio was as small as 1.1.

refractive index method. The output beam is almost circular with an aspect ratio as small as 1.1. A very narrow and circular output beam is obtained. The power dependence from 1 to 20mW at 25°C and temperature dependence from 20 to 70°C at an output power of 3mW of $\theta_{\parallel}$, $\theta_{\perp}$ are shown in Fig. 4*a* and *b*, respectively. Stable output beam characteristics against output power and operating temperature are confirmed.



a

b

Fig. 4 *Output power dependence (1 – 20mW) and temperature dependence (20 – 70°C) of FFPs parallel and perpendicular to junction plane*

FFPs are quite stable against the output power and operating temperature
a Output power dependence
b Temperature dependence

Conclusion: A low threshold current of 14mA, high output power of 30mW with a high differential quantum efficiency of 45% were obtained for a 1.3µm MFC-LD entirely grown by MOCVD. The FWHMs of FFPs parallel and perpendicular to the junction plane are as narrow as 10 and 11°, respectively. It is experimentally verified that a narrow and circular output beam is stable for wide output power and temperature ranges.

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Record low-threshold index-guided InGaAs/GaAlAs vertical-cavity surface-emitting laser with a native oxide confinement structure

Y. Hayashi, T. Mukaihara, N. Hatori, N. Ohnoki, A. Matsutani, F. Koyama and K. Iga

Indexing terms: Vertical cavity surface emitting lasers, Semiconductor lasers

An index-guided InGaAs/GaAlAs vertical-cavity surface-emitting laser with a native oxide confinement structure has been proposed and fabricated. A record threshold current of 70µA was achieved with a 5µm-diameter core device. The proposed structure provides strong electrical and optical confinements. Also a reduction in nonradiative recombination and an improvement in the thermal resistance can be expected.

Arranged light sources with high reliability, low power consumption and mass production capability are needed for use in the future optoelectronics systems including optical interconnection and networking [1]. Low threshold InGaAs/GaAlAs vertical-cavity surface-emitting lasers (VCSELs) are attractive for these applications. Recently, several demonstrations of low-threshold VCSELs were reported [2, 3]. One of the key issues in realising high-performance MOCVD-grown VCSELs is to achieve low power consumption. A record low-threshold current of 91µA in a single-quantum-well VCSEL grown by molecular beam epitaxy (MBE) [4] and a record low-threshold voltage of 1.33V in a VCSEL grown by metal organic chemical vapour deposition (MOCVD) [5] were demonstrated by using an oxidation technique. We have fabricated InGaAs/GaAlAs VCSELs with an etched mesa structure grown by MOCVD, and a threshold current of 0.33mA was achieved for a 6 µm-diameter device in the active region diameter [6]. In general, with decreasing active region volume, ultralow-threshold operation can be expected until we reach the limitation of optical confinement in the active region. However, some crucial problems on optical and electrical confinements and excess heating may limit the size reduction. Recently, a novel oxidation process has been proposed and demonstrated for the purpose of current confinement [4]. We would like to propose a novel Al oxidised cladding, which includes a strong lateral optical confinement and greatly contributes to low-threshold operation and single-fundamental-mode operation for low-noise applications. Significant spatial singlemode operation with high injection level was demonstrated by using antiguided BH VCSELs [7], but this may produce higher optical losses. Oxidised transverse cavities with index-guiding VCSELs, on the other hand, may produce better transverse mode control compared with air-post and antiguiding VCSELs. In this Letter a record low-threshold current of 70µA for an index-guided InGaAs/GaAlAs VCSEL has been achieved under room-temperature continuous-wave (CW) operation with a 5μm-diameter active region which was reduced from 20μm mesa size by using the oxidation technique.

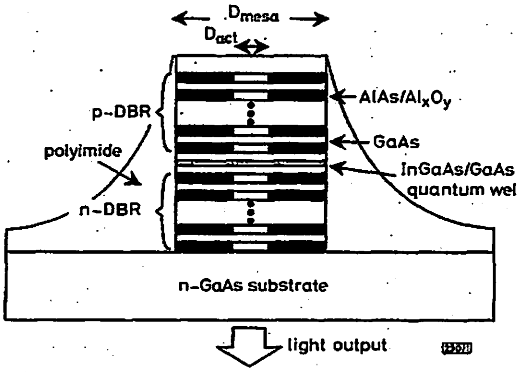

Fig. 1 *Schematic diagram of fabricated InGaAs/GaAlAs VCSEL with native oxide confinement structure*

Fig. 1 shows a schematic diagram of a fabricated InGaAs/GaAlAs VCSEL with an oxide confinement structure. The epitaxial layer was grown by low-pressure MOCVD at 700°C on a GaAs (100) substrate. The active region consists of three 80Å-thick strained $In_{0.2}Ga_{0.8}As$ quantum wells sandwiched by 100Å-thick GaAs barriers. The active region is sandwiched by $Al_{0.4}Ga_{0.6}As$ layers which form separate-confinement heterostructures (SCH) for the vertical carrier confinement. Both the GaAs/AlAs DBRs consisting of periodic quarter-wavelength (λ/4) stacks provide highly reflective mirrors, resulting in low-threshold operation. The top (Zn-doped) mirror has 20 periods with 180Å linearly graded layers at GaAs/AlAs heterojunctions for low series resistances. The bottom (Se-doped) mirror with GaAs/AlAs abrupt interfaces has 22.5 periods. We have introduced modulation doping with high and low carrier concentrations with $3 \times 10^{18}cm^{-3}$ in AlAs and $10^{18}cm^{-3}$ in GaAs layers at both side mirrors, respectively. Circular mesas with 20μm-diameter and 40μm-diameter active regions were formed by Cl_2-based reactive ion beam etching (RIBE). The detail of the RIBE process was as published in [8]. The employed process for oxidising entire AlAs layers of DBR is shown as follows. After the RIBE process, samples were annealed at 400°C under the nitrogen gas bubbled through 80°C water. The annealing time was 5min for a 20μm-diameter device and 10min for a 40μm-diameter device. The active region diameters were reduced from 20 to 5μm and 40 to 20μm, respectively. The fabricated structure is substantially different from [4] and [5]. This may also exhibit a significant index-guiding consisting of a GaAs/AlAs core and GaAs/Al_xO_y cladding [9].

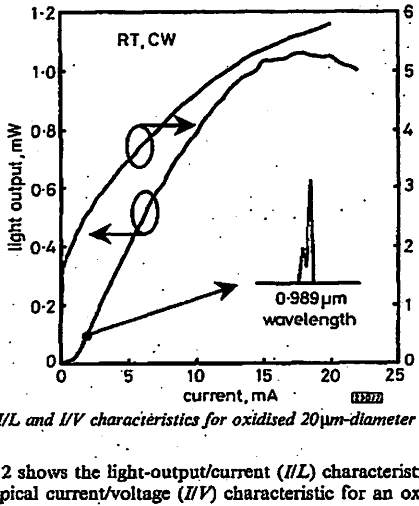

Fig. 2 *I/L and I/V characteristics for oxidised 20μm-diameter device*

Fig. 2 shows the light-output/current (*I/L*) characteristic as well as a typical current/voltage (*I/V*) characteristic for an oxidised 20 μm-diameter device. The inset Figure shows the lasing spectrum at 2.0mA. A threshold current of 0.75mA was achieved, which corresponds to a threshold current density of $300A/cm^2$. A realisation of this low-threshold current density might be partly due to the suppression of nonradiative recombination current at the etched sidewall. Other improvements in threshold voltage lower than 2.0V and a power output exceeding 1mW were achieved due to the suppression of excess heating. We believe that the proposed structure improves the overall performance of VCSELs.

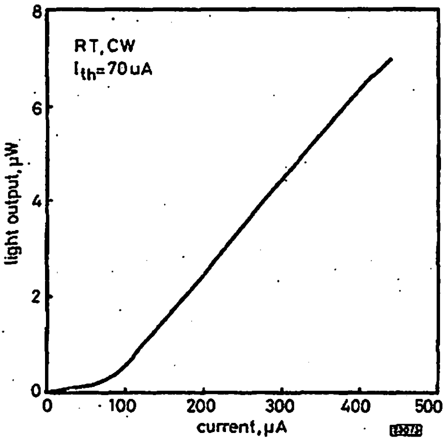

Fig. 3 *I/L characteristic for oxidised 5μm-diameter device*

Fig. 3 shows the *I/L* characteristic for an oxidised 5μm-diameter device. A record threshold current of 70μA was achieved. Because the corresponding threshold current density is as low as $360A/cm^2$, further reduction of threshold current will be expected. Further optimisations could result in submicroampere VCSELs by reducing the diameter.

In conclusion, an index-guided InGaAs/GaAlAs VCSEL with an oxidation confinement structure has been demonstrated. A record threshold current of 70μA was achieved for a 5μm oxidised device. These low power consumption performances are essential for future 2-D optical systems with density-packed VCSELs.

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Wavelength shift in vertical cavity laser arrays on a patterned substrate

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Indexing terms: Semiconductor laser arrays, Vertical cavity surface emitting lasers

The authors demonstrate a spatially chirped emission wavelength in vertical cavity surface emitting laser (VCSEL) arrays grown by molecular beam epitaxy. The wavelength shift is due to a lateral thickness variation in the $Al_{0.2}Ga_{0.8}As$ cavity, which is induced by a substrate temperature profile during growth. A 20 nm shift in lasing wavelength is obtained in a VCSEL array.

Vertical cavity lasers (VCSEL) are attractive devices for parallel optical interconnects for computers [1] and information systems [2]. Using wavelength division multiplexing (WDM) architectures, either the information [3], or the address [4] is encoded using wavelength. A multiwavelength array is an important device for such systems. Because the VCSEL operates in a single longitudinal mode, it is uniquely suitable for making such multi-λ arrays. The lasing wavelength of a VCSEL can be varied by altering the effective cavity length [5 – 8]. A single chirp in wavelength across a VCSEL array was demonstrated [5] by making use of the nonuniformity in the crystal growth system. Recently, multi-λ VCSEL arrays have been fabricated using special post-growth processing [6], and nonplanar MOCVD growth techniques [7]. In this work, we control the cavity thickness variation by a lithographically defined pattern on the back side of the substrate [8]. The backside pattern induces a substrate temperature profile, which in turn controls the GaAs growth rate. This technique allows the fabrication of a large number of multiwavelength arrays with repeatable wavelength on the same wafer. The wavelength variation is fixed during growth, and thus, standard processing techniques are used to fabricate the arrays. We have achieved a VCSEL wavelength shift of 20nm over a 2mm array.

The VCSEL layer structure is grown by molecular beam epitaxy (MBE). Before growth, we define a 200µm deep, 11mm wide, pattern on the wafer backside using wet chemical etching. We then solder the substrate to another GaAs wafer using indium. Owing to the increased thermal contact between the wafers where there is indium, we expect an increased substrate temperature, and thus a lower GaAs growth rate, in these regions. Using this technique [8], we have previously obtained an 8nm periodic mode shift across a wafer in a Fabry-Perot filter. On the n^+ GaAs substrate we grow $22^1/_2$ pairs of AlAs/GaAs quarter wave mirrors ($T_s = 600°C$, $N_d = 4 \times 10^{18} cm^{-3}$), an $Al_{0.2}Ga_{0.8}As$ spacer ($T_s = 700°C$, $N_d = 3 \times 10^{18} cm^{-3}$, three undoped 50 Å $In_{0.2}Ga_{0.8}As$ quantum wells with 50Å GaAs barriers ($T_s = 500°C$), an $Al_{0.2}Ga_{0.8}As$ spacer ($T_s = 700°C$, $N_a = 3 \times 10^{18} cm^{-3}$), 18 pairs of AlAs/GaAs quarter wave mirrors ($T_s = 600°C$, $N_a = 4 \times 10^{18} cm^{-3}$), and a phase matching layer during which we increase the doping level to $N_a = 10^{19} cm^{-3}$. The combined thickness of the AlGaAs spacers and the InGaAs/GaAs wells and barriers add up to one full wavelength cavity at 950nm. To have sufficient time to ramp down the substrate temperature, we interrupt growth for 1min before the quantum wells. The mirror interfaces are linearly graded over 150Å to reduce the series resistance of the structure [9].

After growth, we fabricated broad area 40µm² devices spaced by 180µm. We used Ti/Au both as a top contact and as an etch mask, and etched through the active region using wet chemical etching. The lasers were then probe tested with 200 ns current pulses and the light was collected through the substrate. Threshold currents were 70 – 80mA throughout the high temperature region. We measure an increased threshold with increasing lasing wavelength, which we attribute to an increasing mismatch of cavity mode and gain peak wavelength. We expect to achieve better threshold uniformity with an optimised structure.

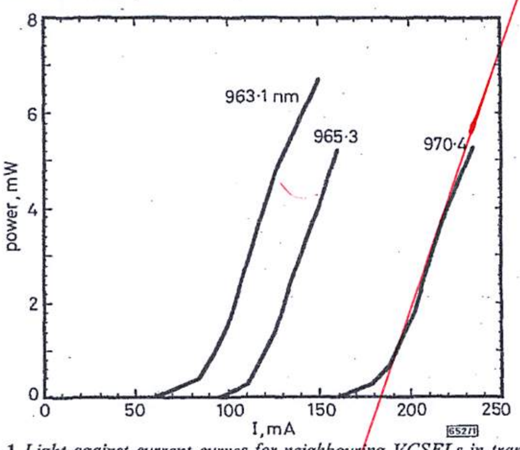

Fig. 1 *Light against current curves for neighbouring VCSELs in transition between hot and cold regions of wafer*

Lasing spectra from two adjacent identical arrays can be seen in Fig. 1. Neighbouring elements exhibit a wavelength shift of ~2nm in the linear region. Near both ends of the array the wavelength separation is somewhat less due to the nonlinear shape of the temperature profile. In Fig. 2, we plot the lasing wavelength for 10 adjacent arrays, which is an indication of the wavelength uniformity. In the high temperature region, the wavelength is uniform near 963nm. Across the transition to the colder region, the lasing wavelength is blue-shifted 20nm over a 2mm region, at a maximum rate of 14nm/mm. The average standard deviation in laser wavelength for a given laser in the array is 0.9nm. The maximum deviation is 1.3nm, which occurs near the centre of the array. Although these deviations are not small enough for many WDM systems with narrow channel spacings, it is well within range for a wavelength coded switching network [4]. The wavelength varation can be further improved by improving the thermal contact to the patterned substrate.

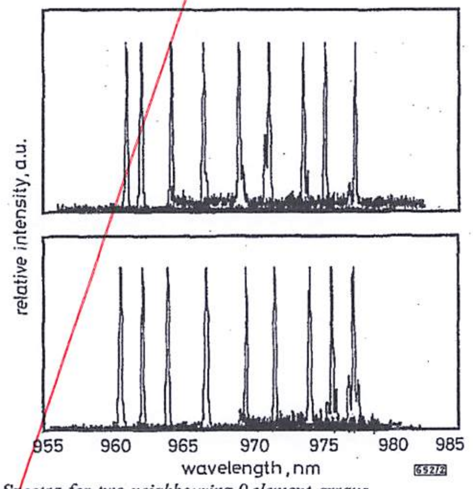

Fig. 2 *Spectra for two neighbouring 9 element arrays*

It is very difficult to control the absolute growth rate of GaAs during high temperature MBE growth by relying only on the substrate thermocouple temperature and calibration curves. Because the rate is very sensitive to substrate temperature in this regime, a small variation in temperature will give rise to unacceptably large thickness differences. To obtain the necessary growth rate precision at high substrate temperature, it is therefore necessary to directly measure, or monitor, the growth rate [10, 11] during growth. Here, we have corrected for the offset in our grown cavity to match the designed thickness after the second $Al_{0.2}Ga_{0.8}As$ spacer layer as in [10].