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Low-threshold mesa-etched vertical-cavity InGaAs/GaAs surface-emitting lasers grown by MOCVD

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Indexing terms: Vertical cavity surface emitting lasers, Heat transfer

The authors have demonstrated a low threshold current of 0.33 mA and a threshold current density of 380A/cm^2 for MOCVD-grown InGaAs/GaAs vertical-cavity surface-emitting lasers with a pillar etched structure. The thermal characteristic of the fabricated device including thermal resistance and junction temperature rise is also discussed. Judging from this experiment, further reduction of threshold current can be expected by reducing nonradiative recombination and electrical resistance.

Low threshold current vertical-cavity surface-emitting lasers (VCSELs) [1] have been rapidly developed as one of the key devices for future optical integrated systems with two-dimensional configuration. Also their ease in wafer-scale fabrication and testing makes them suitable for mass production. Several reports have been published on low threshold current VSCELs with various structures grown by molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD) [2 – 7]. A record threshold current of 91μA for MBE-grown single-quantum-well VCSELs has been demonstrated using the selective oxidation technique. As well as low threshold characteristic, the thermal properties including the thermal resistance and the CW operating temperature range are important factors in realising temperature-insensitive VSCELs [8, 9]. In long-wavelength VCSELs, some efforts to solve the thermal problems were conducted, for example, using thermally conductive mirrors [10]. In this Letter we have demonstrated a low threshold current of 0.33mA and a threshold current density of 380A/cm^2 with 6 and 20μm-diameter devices, respectively. These are record performances for MOCVD- grown mesa-etched VSCELs. The thermal resistance of low-threshold VCSELs is also estimated for further size reduction.

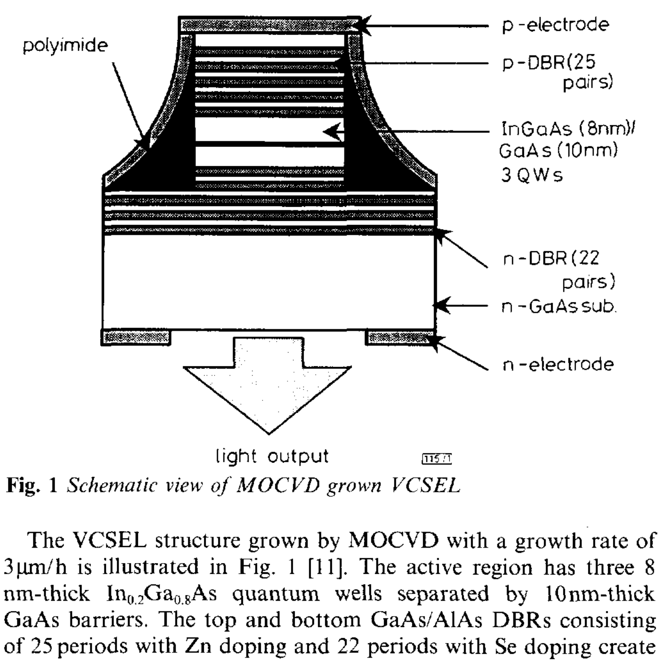

Fig. 1 *Schematic view of MOCVD grown VCSEL*

The VCSEL structure grown by MOCVD with a growth rate of 3μm/h is illustrated in Fig. 1 [11]. The active region has three 8 nm-thick $In_{0.2}Ga_{0.8}As$ quantum wells separated by 10nm-thick GaAs barriers. The top and bottom GaAs/AlAs DBRs consisting of 25 periods with Zn doping and 22 periods with Se doping create a high reflectivity of more than 99%. To reduce the electrical resistance, MOCVD systems enable us to easily form linear graded layers introduced in the heterojunction. The pillar etched mesa structure is formed by a reactive ion beam etch or wet etch. Since this current confinement structure provides a strong carrier confinement as well as optical confinement in the active region, an ultralow threshold operation can be expected by reducing the size to a few micrometres. The *I/L* characteristics of 6, 10 and 20μm-diameter devices measured under room-temperature CW conditions are displayed in Fig. 2. Low threshold current of 0.33, 0.5 and 1.2mA were obtained for the devices with the aforementioned different sizes in order. The corresponding threshold current densities were 1170, 640 and 380A/cm^2. The 6μm device shows a fundamental transverse mode operation. The mode suppression ratio of the 1st-order transverse mode is 35dB at I/I_{th} = 3.2. The output power was limited in the range of 0.1mW due to the use of the highly reflective mirror because we focused on the reduction of threshold current in this experiment. These low-threshold VCSEL results indicate good wafer quality in the employed MOCVD growth.

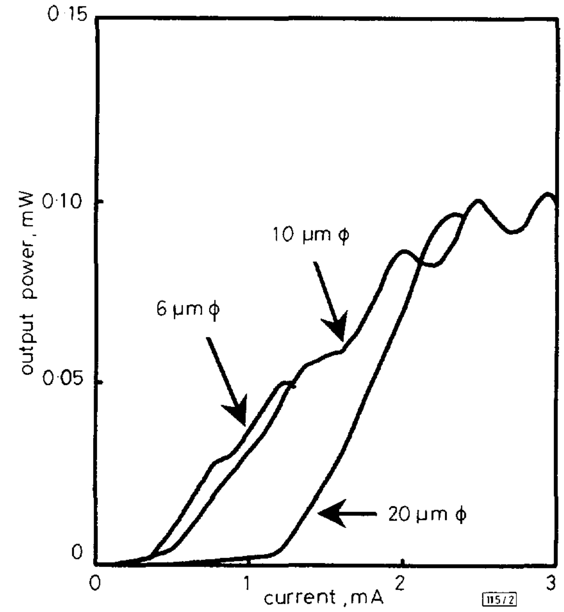

Fig. 2 *Light/current characteristics for 6, 10 and 20μm-diameter VCSELs*

A slight increase in threshold current density observed in smaller devices might be caused by nonradiative recombination and excess heating in the *p*-mirror originating from threshold voltages higher than 2.5V. Surface recombination velocity is examined by using the following equation [12]:

$$J_{th} = N_w d n_{th} q(2V_s/r + 1/\tau)$$

where N_w is the number of wells, d is the well thickness, n_{th} is the threshold current density, r is the device radius and τ is the radiative carrier lifetime. The fitting curve based on the above equation determines the surface recombination velocity V_S to be 1×10^5cm/s. The improvement in surface condition by sulphide passivation [12] and reduction of electrical resistance will be helpful for further threshold reduction.

The temperature rise due to the heating at mirrors may become a crucial issue, especially in smaller devices when trying to realise ultralow-power consumption. We show the thermal behaviour to be dependent on the device size of VCSELs. The thermal resistance is estimated by evaluating the wavelength shift with increasing electrical power. The wavelength shift as a function of the dissipated power for 6, 10 and 20μm-diameter devices was measured. The measured lasing wavelength shifts were 3, 1.3 and 0.8Å/mW, respectively. When we assume the temperature dependence of the lasing wavelength to be 1.0Å/K, the estimated thermal resistances are 3, 1.3 and 0.8K/mW, respectively. They are summarised in Fig. 3 with the calculation based on the simple equation [13]

$$R_{th} = \sum_i t_i/S\sigma_i$$

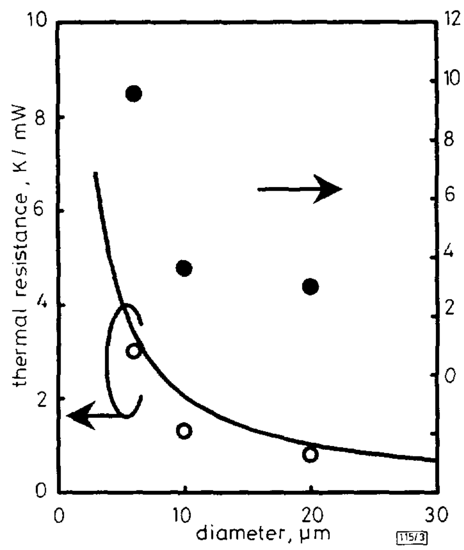

Fig. 3 *Thermal resistance and temperature rise at threshold against device size of VCSEL*

where t_i and σ_i are the thickness and conductivity of the ith layer, and S is the device area. The experimental results are in agreement with the calculation, neglecting the heat flow toward the substrate side. In Fig. 3 we also show the temperature rise at the threshold according to the equation [14]

$$\Delta T = R_{th} P_d$$

where P_d is the electrically dissipated power at threshold. The temperature rise seems to be higher in the smaller devices due to their high threshold voltage. The increase in junction temperature sometimes exacerbates the mismatching of the gain and cavity mode, resulting in further increases in threshold current. This cycle accelerates deterioration of the VCSEL performance. The reduction of electrical resistance in DBRs and power dissipation are important for realising temperature-insensitive VSCELs.

In conclusion, we have achieved a very low threshold current of 0.33mA and a threshold current density of 380A/cm² for 0.98μm VCSELs grown by MOCVD. We have also estimated the thermal resistance and its dependence on device diameter. Further reduction of the power consumption can be expected by making the device smaller with suitable surface passivation as well as by reducing the p-mirror resistance.

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Singlemode 1.3μm Fabry-Perot lasers by mode suppression

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Indexing terms: Semiconductor junction lasers, Laser modes, Crystal defects, Ion beam effects

Focused Ga^+ ion beam etched pits are used to simulate defects, reflective and nonradiative, in conventional 1.3μm Fabry-Perot lasers. Combination of three defect sites positioned along the lasing filament results in a quasi-singlemode laser with 30dB mode suppression and negligible rises in threshold current. The authors also report the appearance of a single enhanced spectral line below threshold.

Introduction: Advancement in optical communication systems requires greater control over the optical spectra of semiconductor laser diodes. Understanding the physics of the spectra of Fabry-Perot lasers, coupled with the ability to sculpture the modes, allows the fabrication of lasers with 'made to measure spectra'. Original experiments [1] using laser ablation to create defect sites resulted in a large increase in threshold current, 60% to 300% per defect. However, we have shown [2] using focused ion beam etching, FIBE, that our single defect sites give rise to relatively small increases in threshold, while producing mode modulation with 40 dB of suppression.

In this Letter we extend our work to multietched pits and have engineered a quasi-singlemode laser with a sidemode suppression ratio of 30dB, using a minimum of three defect sites. The resulting increase in threshold current is small but can, however, be reduced with annealing.

We also report the appearance of a single enhanced spectral line 7dB above the spontaneous emission level at drives 20% below threshold.

Principle: Scattering losses exist in all waveguide structures [3] and they play an important role in determining the spectral output of Fabry-Perot lasers. These scattering centres arise from defects, imperfections, nonuniformities and surfaces which are not atomically smooth and we approximate their behaviour with etched pits.

If a reflecting *or* absorbing defect is placed within the laser waveguide structure at a distance $x = l/2^n$ from the end of one facet, where n is an integer (for simplicity), then scattering caused by this defect will result in a perturbation in the gain profile. This results in the periodic modulation of the spectral envelope with a