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Low Threshold Current Density and High Efficiency Surface-Emitting Lasers with a Periodic Gain Active Structure

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CONTENTS

ABSTRACT

We have achieved very low threshold current densities with high light output powers for InGaAs / GaAs surface-emitting lasers using a periodic gain active structure in which three quantum wells are inserted in two-wavelength-thick (2λ) cavity. Air-post type devices with a diameter of 20~40 μm exhibit a threshold current density of 380~410 A/cm^2. Output power for a 40 μm diameter device reaches over 11 mW. A simple theoretical calculation of the threshold and power performances indicates that the periodic gain structure has an advantage in achieving low threshold current density mainly due to the high coupling efficiency between gain medium and optical field. The deterioration of power, expected from the long cavity length of 2λ, is negligible.

I. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are attractive as light sources for future optical parallel processing, optical communications and optical interconnections. The most important issues to open the wide application area are to improve threshold current and light output power performances. However, threshold current and output power have some conflicting dependencies on each other. Most of the devices with submilliamp threshold current (0.47∼0.8 mA) have shown relatively low output power (0.2∼1.2 mW) and low differential quantum efficiency (4∼32%) [1]-[4]. The unit device that recorded highest output power with a peak power greater than 100 mW operated at a very high threshold current over 10 mA [5]. The only result that achieved both submilliamp threshold current and high quantum efficiency is the report of Scott *et al.* [6]. They showed a threshold current of 0.7 mA and an efficiency of 46% by improving the contact formation and the scheme of current blocking layer. The threshold current density of this device, however, showed a relatively high value of 1870 A/cm^2. The difficulty in achieving low threshold and high power performances simultaneously is attributed to contrary dependencies of threshold current and output power on design parameters of the VCSEL structure. One of the significant dependencies is that while the enhancement of the reflectivity of the distributed Bragg reflector (DBR) reduces the threshold current, it also causes the reduction of light output power.

Recently, we reported a periodic gain VCSEL structure with both low threshold current and high differential quantum efficiency [7]. The periodic gain structure has the advantage of more effective coupling between the gain regions and the internal optical field. The enhancement of the coupling efficiency contributes to the reduction of threshold current density without deteriorating the output power characteristics. In this paper, we present detailed experimental results as well as the calculated characteristics for the periodic gain structure.

II. STRUCTURAL DESIGN

We calculated device performance as the structure of the active region and the cavity are varied to optimize the threshold current and output power. We assume that bimolecular recombination has a dominant contribution to the threshold current. For a device in which the active layers are buried in cladding layers with larger bandgap energy, the threshold current density J_{th} can be expressed as follows using a linear gain approximation [8]:

$$\begin{aligned} J_{th} = edB_{eff}[&\alpha_{eff}L_{eff}/(L\xi A_o) \\ &+1/(2L\xi A_o)\ln(1/R_tR_b)+N_{tr}]^2, \end{aligned} \tag{1}$$

where e is electron charge, d is the total thickness of quantum wells, B_{eff} is the bimolecular recombination constant, A_o is the differential gain coefficient, L_{eff} is the effective cavity length including the penetration depth in the mirrors, α_{eff} is the effective absorption loss in the effective cavity region, L is the cavity length, ξ is the confinement factor, R_t and R_b are respectively the reflectivities of the top and bottom reflectors, and N_{tr} is the transparent current density. If the confinement factors for transverse modes in x and y directions are unity, ξ in (1) for the active quantum wells with a uniform thickness of t in the z direction is approximately given by, [8]

$$\xi = \sum_{QWs} \int_{-t/2}^{+t/2} \cos^2(kz)\,dz \Big/ \int_{-L/2}^{+L/2} \cos^2(kz)\,dz, \qquad (2)$$

$$= \gamma d/L, \qquad (3)$$

where k is the wave number of the lasing mode. For the periodic gain structure, γ becomes nearly two.

The variation of output power P with current I is expressed as, [9]

$$P = \eta_i h\nu/e \ln(1/R_tR_b)/[2\alpha L + \ln(1/R_tR_b)](I - I_{th})$$
$$= \eta_d h\nu/e(I - I_{th}), \qquad (4)$$

where η_i is the internal quantum efficiency, α is the internal loss, I_{th} is the threshold current, and η_d is the external differential quantum efficiency. Since the power is dependent on the threshold current, as seen in (4), it is difficult to compare the output power performance for given structures by only considering the differential quantum efficiency term. Thus, we compare the output power performance by considering the current required to reach a given power P_c as follows:

$$I_c = P_c/(\eta_d h\nu/e) + I_{th}. \qquad (5)$$

If I_c is low, we can expect a higher output power at the same current.

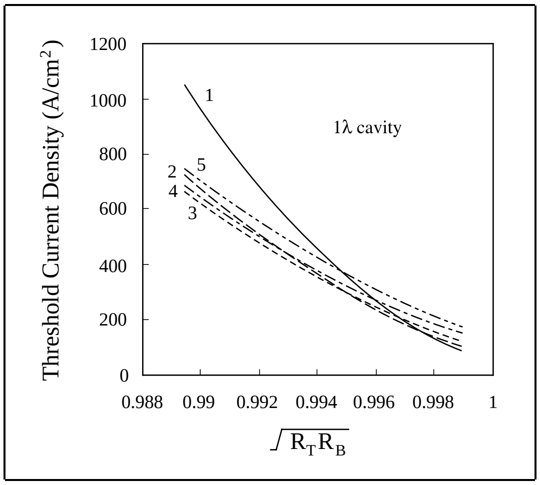

Fig. 1. Threshold current density as a function of the reflectivities of top and bottom mirrors for a 1λ cavity structure with different numbers of quantum wells.

We calculated first the threshold current density as the number of quantum wells embedded in a one-wavelength-thick (1λ) cavity is varied. Figure 1 shows the threshold current density as a function of the reflectivity, calculated from (1). In this calculation, we considered only a single subband for the conduction and valence bands. The confinement factor for each quantum well structure was calculated from (2). We used $B_{eff} = 1 \times 10^{-10}$ cm^3/s for GaAs [8], $\alpha_{eff} = 10$ cm^{-1} and $t = 85\text{Å}$. We put $A_0 = 9.23 \times 10^{-16}$ cm^2 and $N_{tr} = 1.26 \times 10^{18}$ cm^{-3}, which were obtained from the simple two band gain calculation. As seen in Fig. 1, J_{th} is minimized in the three quantum well structure in the range of $(R_t R_b)^{1/2} < 0.995$. Figure 2 shows J_{th} vs reflectivity curves comparing a structure with three closely spaced quantum wells embedded in a 1λ thick cavity and a periodic gain structure with a 2λ thick cavity. Two different values were considered for the loss term ($\alpha_{eff} = 10$ cm^{-1} and $\alpha_{eff} = 20$ cm^{-1}). Figure 2 indicates that the periodic gain structure with a 2λ cavity provides a lower J_{th}, than the 1λ cavity structure in the range of $(R_t R_b)^{1/2} < 0.997$. This result is mainly attributed to the high coupling efficiency in the periodic gain structure, which provides a maximized γ in (2).

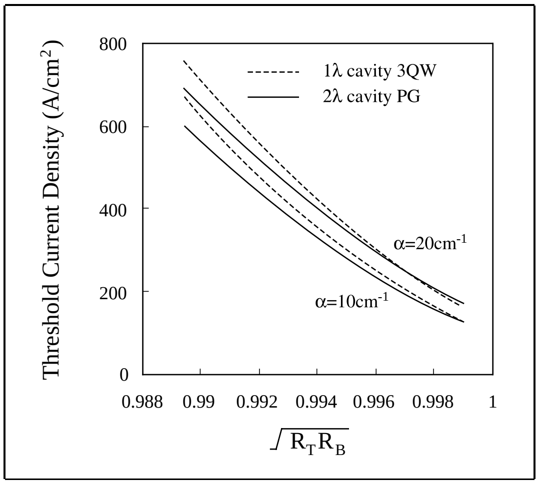

Fig. 2. Threshold current density as a function of the reflectivities of top and bottom mirrors for the structures with three quantum wells in 1λ cavity and 2λ cavity.

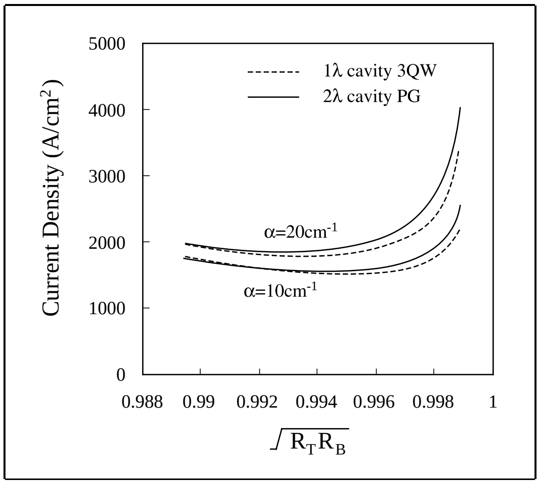

Fig. 3. The current density needed to achieve 1 mW output power for the structures with three quantum wells in a 1λ cavity and a 2λ cavity, respectively.

Figure 3 shows the threshold current densities I_c required to obtain 1 mW light output power in (4) for devices with a 10 μm active area diameter. The internal quantum efficiency was assumed to be unity. In a low reflectivity range (for example $(R_t R_b)^{1/2} < 0.992$ when $\alpha_{eff} = 10$ cm^{-1}), the periodic gain structure has an advantage to obtain higher power performance than the 1λ cavity structure. In a middle reflectivity range ($0.992 < (R_t R_b)^{1/2} < 0.995$), the difference in the power performance between the two structures is negligible. From the calculated data shown in Figs. 2 and 3, we conclude that the periodic gain structure with 2λ cavity has an advantage in achieving a lower threshold current without deteriorating the output power within a reasonable range of the reflectivity ($0.990 < (R_t R_b)^{1/2} < 0.995$).

III. DEVICE FABRICATION

Figure 4 shows a schematic view of the

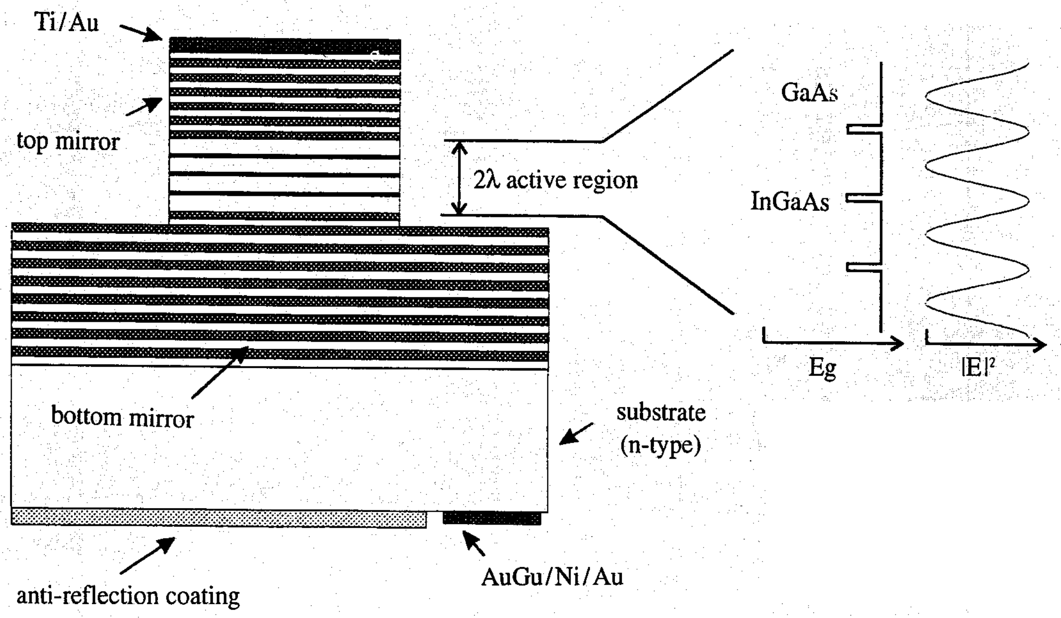

Fig. 4. A schematic diagram showing the epitaxial structure used for the VCSELs in this work.

work. The epitaxial structure was grown by metal-organic chemical vapor deposition. The top (*p*-doped) and bottom (*n*-doped) DBR mirrors consist of, respectively, 16 and 23.5 periods of AlAs/GaAs quarter wave stacks with $Al_{0.33}Ga_{0.67}As$ (200Å) grading layers. An extra p^+-GaAs layer is inserted on the top DBR mirror for phase matching in the reflection at the top metal (Au) contact. The active region consists of three $In_{0.22}Ga_{0.78}As$ (85Å) quantum wells with GaAs spacer layers. Each of the quantum wells is located at the anti-node positions of the standing wave pattern of the optical field in a 2λ cavity. We fabricated bottom-emitting lasers of the air-post, index-guided type, using chemically assisted ion beam etching with chlorine. Figure 5 shows scanning electron micrograph of a typical device. The laser post was etched through the active region to the top layer of the bottom mirror by *in-situ* monitoring of etch depth using laser reflectometry [10]. The process of device fabrication is as follows. The back side of the as-grown epitaxial wafer was first polished and antireflection (AR) layers of TiO_x/SiO_y were deposited at 350 °C. The measured reflectivity after AR coating was less than 0.5%. For *n*-contact on back side of the substrate, the AR layers on the edge of the sample were removed by reactive ion etching using CF_4 and He gases and then AuGe/Ni/Au layers were deposited. The metal layers were alloyed at 370 °C for 20 sec by rapid thermal annealing. For p-contact, Ti (20Å) / Au (3000Å) / Ni (1500Å) metal dots were deposited on top p-mirror. The thin Ti layer was inserted to improve adhesion on the GaAs surface without reduction of the top mirror reflectivity. The Ni layer was deposited to use as a mask layer for the ion-beam etching.

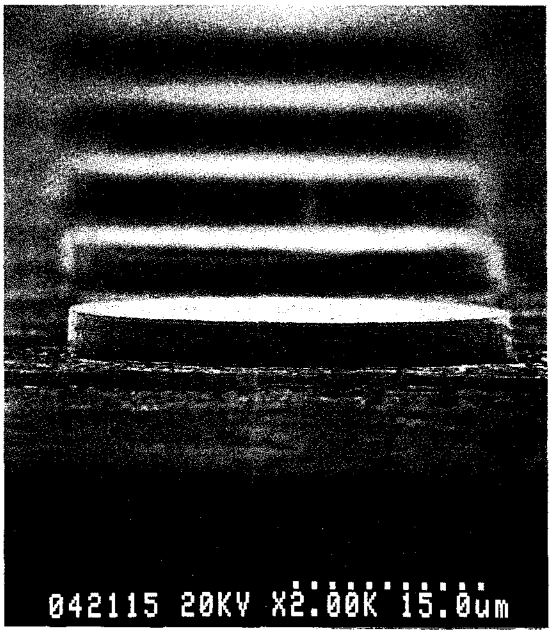

Fig. 5. Scanning electron microscope of a circular airpost VCSEL.

IV. DEVICE CHARACTERISTICS

Figure 6 shows the light output power versus current characteristics measured from CW operation at room temperature. The $L-I$ characteristics were measured without a heat sink. The lasing wavelength was around 991 nm at threshold current and shifts to longer wavelength up to 995 nm with increasing current. Threshold currents for circular devices with 20, 25, 35 and 40 μm diameters are 1.2, 2.0, 3.8 and 4.8 mA, respectively. Maximum light output powers of these devices are, respectively, 3.5, 5, 10 and 11 mW.

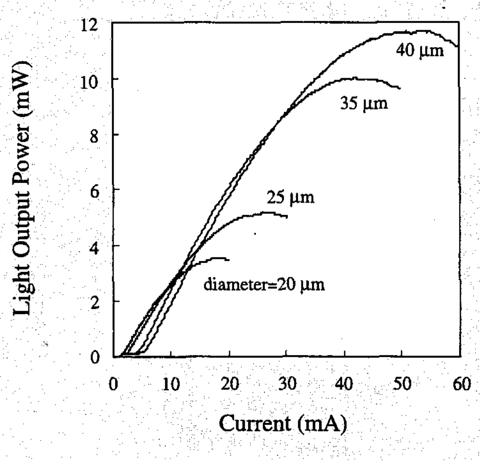

Fig. 6. The CW light output characteristics of VCSELs using a periodic gain active structure with 2λ cavity.

Figure 7 shows the threshold current densities and differential quantum efficiency versus the active area for various sizes of circular and square devices. The lowest threshold current densities for each size larger than 20 μm diameter or width are 370~410 A/cm^2. The external quantum efficiencies are as high as 26~32% with threshold voltages of 1.7~2.4 V. Figure 8 shows wallplug efficiencies of these devices. A peak wallplug efficiency reaches over 11% for a 35 μm diameter device.

The threshold current density seen in Fig. 7 approaches the best values for VCSELs. Re-

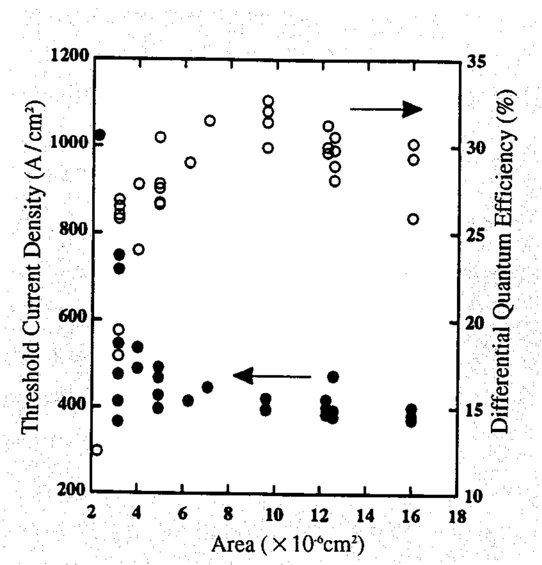

Fig. 7. Threshold current density and differential efficiency against the active area for various sizes of circular and square VCSELs.

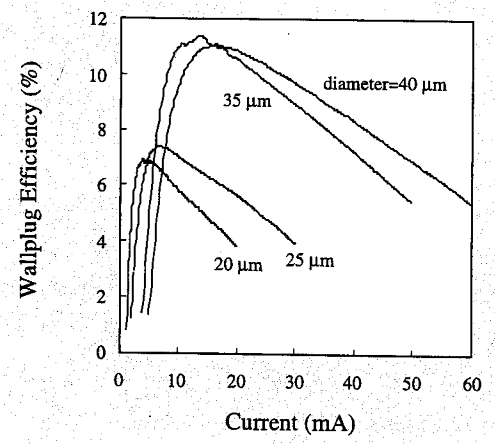

Fig. 8. Wallplug efficiency characteristics of VCSELs.

cently, Deppe *et al.* [11] reported 350 A/cm^2 threshold current density from an InGaAs VCSEL using CaF/ZnSe top mirror layer and lateral oxidation of a surface AlAs layer on the active cavity. Their threshold current data were obtained from a 7 μm square device with a threshold current of 225 μA. The low threshold current obtained in their work is mainly attributed to the CaF/ZnSe mirrors which can provide high contrast reflectivity and also to the passive aluminium oxide surrounding the first AlAs mirror layer on the active region, which can provide highly efficient current injection into the active region. The threshold current characteristic is critically affected by the surface states of the index-guided cavity, in particular for small size devices. Even though our air post devices are not processed by any surface passivation, they show comparable threshold current density to the best data, and have moderately high differential quantum efficiencies. Compared to the data obtained from as-etched air-post devices, our data for the threshold current density and power are the best results. Sugimoto *et al.* [12] reported a threshold current density of 450 A/cm^2 in a device with 1λ cavity periodically doped DBR structure. In a recent work of Yoffe *et al.* [13], a threshold current density of 380 A/cm^2 was reported using a structure with 2λ cavity and *in-situ* grown Al top contact. The latter data is comparable with our data, but the maximum output power of this device is several times less than our results. In Fig. 7, an increase of the threshold current density is seen for the small devices below 20 μm square. This tendency must be attributed to the increase of surface recombination currents with decreasing device size. Thus, by improving surface treatment of the etched side wall, we expect to obtain lower threshold currents for smaller devices.

The low threshold current densities in our results are believed to be attributed to the periodic gain active structure, as predicted in Fig. 2. The periodic gain structure can give more effective coupling between the gain medium and the internal optical field. As expected in Fig. 3, the periodic gain devices fabricated in this work provided also moderately high light output powers. Several similar periodic gain VCSELs with our structure have been studied. Yoffe *et al.* [13] showed a comparable threshold current with our data as cited above. In the work of Sale *et al.* [14], a low threshold current density of 366 A/cm^2 was obtained from pulse operation. These results suggest that the periodic gain structure would be efficient for the VCSEL characteristics.

On the other hand, the periodic distribution of strained wells can give also an advantage in epitaxial growth for the VCSEL structure having compressive multiple quantum wells such as the InGaAs/GaAs system. The critical thickness for the growth of a tensile layer without strain relaxation is calculated to be 3$\sim$5 times smaller than that for the growth of a compressive layer undergoing the same misfit [15]. This tendency implies that the tensile layer is easily relaxed and troublesome in strain control, rather than the compressive layer. In multiple layer structure, misfit strain between neighboring layers is shared in inverse ratio of the film thickness. Thus, in the 1λ cavity structure, if multiple quantum wells are closely inserted near the gain peaks, the GaAs barrier becomes thin and suffers a large tensile strain. Such strain distribution eventually limit the increase in the strain and layer thickness of the compressive wells. In a periodic gain structure, where the compressive wells are separated by a sufficient distance, the strain is concentrated in the compressive layers which possess much higher resistance against the strain relaxation than the tensile barriers. Such strain distribution allows more strained InGaAs wells to be embedded in the cavity and gives an advantage of achieving high-power devices [13]. However, the periodic gain structure requires a precise control of the layer thickness in epitaxial growth to locate each well exactly at a gain peak to obtain high coupling efficiency.

V. SUMMARY

We have demonstrated a periodic gain surface-emitting laser structure in which three InGaAs strained quantum wells are distributed at the antinode positions of the internal optical field in 2λ cavity. The air-post type devices demonstrated very low threshold current densities of 380 - 410 A/cm^2 with moderately high external differential quantum efficiencies. This result indicates that the periodic gain active structure is useful in improving the threshold characteristics of VCSELs without deteriorating the light output power characteristics.

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