Surface Emitting Semiconductor Lasers

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***Abstract*—A surface emitting laser is very attractive for lightwave communication as well as optoelectronics when taking advantage of the possible two-dimensional arrayed configuration.**

In this paper, we describe the research progress of developing a vertical cavity surface emitting (SE) injection laser based on GaAlAs/GaAs and GaInAsP/InP systems. Ultimate laser characteristics, device design, state-of-the-art performances, possible device improvement, and future prospects will also be discussed.

The authors proposed a vertical cavity surface emitting semiconductor laser and currently much work is done in our laboratory to realize it. In order to reduce the threshold current, we have improved the laser reflector and introduced a circular buried heterostructure. The microcavity structure, which is 7 μm long and 6 μm in diameter, was realized with a threshold of 6 mA. Thus, possibilities of an extremely low threshold current SE laser device and a densely packed two-dimensional array are suggested.

I. Introduction

THE importance of semiconductor lasers is rapidly increasing along with the progress of optoelectronics fields such as optical fiber communication and optical disk memories. However, in the present structure of cleaved semiconductor lasers, there are still some problems, e.g., the initial probe test of such devices is impossible before separating into chips, the monolithic integration of lasers into an optical circuit is limited due to the finite cavity length, and so on. The authors suggested a vertical cavity surface emitting (SE) laser in 1977 for the purpose of overcoming such difficulties as mentioned above. Fig. 1 shows the Fabry–Perot resonator in the SE laser formed by two surfaces of an epitaxial layer; the light output is taken from the surface of a substrate vertically. Accordingly, this scheme of laser structure, if realized, may provide many novel advantages.

1) The laser device is fabricated by a fully monolithic process.

2) A densely packed two-dimensional laser array could be fabricated.

3) The initial probe test could be performed before separation into chips.

4) Dynamic single longitudinal mode operation is expected because of its large mode spacing (= 100–200 Å).

5) It is possible to vertically stack multithin-film functional optical devices on to the SE laser.

6) A narrow circular beam is achievable.

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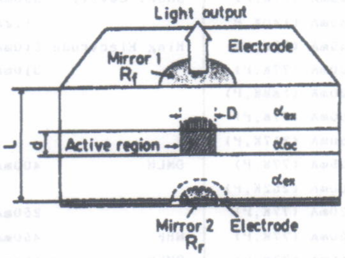


Fig. 1. A schematic diagram of a surface emitting laser. Mirror 1 is comparatively large compared with a mode spot size. The diameter of mirror 2 is the same as that of the active region.

A laser structure where the emission is taken out perpendicular to the electrode was demonstrated by Melngailis with a bulk InSb at 10 K under an intense magnetic field [1]. The authors have been developing a vertical cavity SE laser with GaInAsP/InP and GaAlAs/GaAs systems [2]–[20]. It is advisable for a long-haul optical fiber communication system to use the GaInAsP/InP SE single-mode laser emitting within the 1.3 or 1.5 μm wavelength region. On the other hand, GaAlAs SE lasers are attractive for optical disks, optical sensing, and optical parallel processing. We obtained the first lasing operation of a GaInAsP/InP SE laser in 1979 when the threshold was 900 mA under a pulsed condition at 77 K [2]. We also obtained a room temperature pulsed operation in a GaAlAs/GaAs SE laser in 1983 [15].

In experimental SE lasers, threshold current densities were rather high in comparison with a conventional stripe laser. The length of the gain region is quite short (2–3 μm) preventing room temperature continuous wave (CW) operation of SE lasers. According to research on SE lasers in the authors' group up to now, we have recognized the following points as especially important in order to reduce the threshold current of a vertical cavity SE laser:

1) high reflectivity of laser mirrors ($R > 95$ percent),

2) effective current confining structure.

In a preliminary structure [2], a gold–zinc alloy mirror was simply used for a laser reflector and also served as an electrode. Therefore, the reflectivity was poor ($R < 0.8$), which caused a rather high threshold. To increase reflectivity of the p-side (bonding side) reflector, we introduced a ring electrode where the reflecting mirror is separated from the electrode [7]. In addition to this we introduced a Au/SiO_2 mirror [11], or dielectric multilayer reflector [16], for improvement in the n-side (output side) reflectivity. For the purpose of effectively confining current in an active region, some types of current confining structures were introduced, i.e., a round-low mesa, round-high

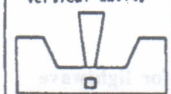
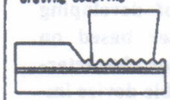
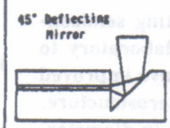
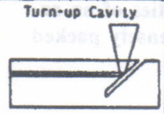
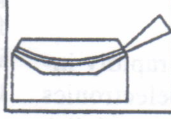
File 2.

TABLE I
PROGRESS OF OUR SE LASER RESEARCH

	GaInAsP/InP SE laser		GaAlAs/GaAs SE laser	
1977	Suggestion			
1979	Planar	900mA (77K,P)	P: Pulse	
1981	BH	520mA (77K,P)	CW: Continuous wave	
	PBH	800mA (77K,P)		
1982	Short Cavity	160mA (77K,P)		
1983	Window/Cap	50mA (77K,P)	Short Cavity	350mA (77K,P)
		180mA (140K,P		1.2A (293K,P)
1984	Two Act.	145mA (77K,P)	Ring Electrode	510mA (293K,P)
	Ring Electrode	90mA (77K,P)		310mA (293K,P)
		720mA (188K,P)		
	Low-Mesa	60mA (77K,P)		
		450mA (217K,P)		
1985		35mA (77K,P)	DMLR	400mA (293K,P)
		700mA (252K,P)		
	DBR	120mA (77K,P)		250mA (293K,P)
	PBH	250mA (77K,P)	MBE	450mA (293K,P)
	HMPB	85mA (77K,P)	DMLR	150mA (293K,P)
		600mA (225K,P)		
	DMLR	65mA (77K,P)		
	Au/SiO_2	18mA (77K,P)		
		400mA (263K,P)		
1986	CBH	24mA (77K,P)	CBH	68mA (293K,P)
	FCBH	20mA (77K,P)		6mA (293K,P)
				4.5mA (77K,CW)
			MOCVD	300mA (293K,P)
1987	CBH	15mA (77K,CW)	MOCVD-CBH	50mA (293K,P)
				55mA (160K,CW)
1988	FCBH	12mA (77K,CW)	MOCVD-CBH	40mA (293K,P)
				50mA (230K,CW)

HMPB: High-Mesa/Polyimide-Buried
DMLR: Dielectric Multilayer Reflector
PBH: Planar Buried Heterostructure
CBH: Circular Buried Heterostructure
FCBH: Flat Surface Circular Buried Heterostructure

TABLE II
FUNDAMENTAL CHARACTERISTICS OF SOME TYPES OF SURFACE EMITTING LASERS

	Laser Characteristics	2D Laser Array Capability	Coupling with Other Devices
Vertical Cavity 	• Narrow circular beam divergence • Single mode operation	• Free arrangement • Dense packing	Vertical stacking
Horizontal Cavity			
Grating Coupling 	• Limited efficiency • Narrow beam in one direction	Limited by cavity length	Beam angle sensitive to the change of wavelength
45° Deflecting Mirror 	• Compatible with conventional structure • Beam quality dependent on mirror flatness	Limited by cavity length	Similar to stripe lasers
Turn-up Cavity 	Limited equivalent reflectivity	Limited by cavity length	Similar to stripe lasers
	• Simple to manufacture	Difficult due to oblique output beam	Similar to stripe lasers

mesa/polyimid buried, and circular buried heterostructure [12]. By introducing a circular buried-heterostructure (CBH), the threshold was dramatically reduced and low threshold current room temperature pulsed operation was obtained in a GaAlAs/GaAs system [17], [18]. Table I shows the progress of our SE laser research.

On the other hand, other types of surface emitting lasers, such as a horizontal cavity and turn-up cavity surface emitters are extensively studied. The horizontal cavity scheme includes a distributed Bragg reflector (DBR) or distributed feedback (DFB) structure employing a higher order coupling grating [21], [22], and a configuration using a 45° deflector [23], [24]. The turn-up cavity structure utilizes an intracavity bent waveguide or deflecting mirror [25], [26]. Several fundamental characteristics of these lasers are summarized in Table II from the viewpoints of laser performance, two-dimensional laser array application, and coupling ability with other devices. In terms of laser performance itself, an extremely low threshold can be expected in a vertical cavity SE laser by introducing a microcavity structure with both a cavity length and active region diameter of several microns. Even if the reflectivity is as high as 95 percent, high differential quantum efficiency comparable to that of conventional stripe lasers can be achieved by using a short cavity structure. In the case of the grating structure, narrow beam divergence can be obtained, but it was wasteful in principle to emit light to the substrate and the efficiency is deteriorated. The optical performance of a 45° deflecting mirror structure strongly depends on the flatness and the angle of the installed reflector. The aberration of the beam may remain a problem. In a turn-up cavity structure, the threshold current may increase due to additional cavity loss.

Taking the two-dimensional array application into account, the vertical cavity structure has more flexibility in its arrangement and thus a densely packed two-dimensional array can be fabricated. The density of a two-dimensional array formed by other structures is limited by the cavity length of about 300 μm. Moreover, the coupling efficiency with other devices can be expected to be highest in the vertical cavity SE laser since it emits a circular narrow beam.

Vertical cavity SE lasers utilizing semiconductor multilayer reflectors for such as a DBR [9] or DFB structure [27] may enable the integration of thin film functional optical devices on to an SE laser by stacking them. This will open up a new three-dimensional integrated optics [28]. Such a thin multilayer structure can be obtained by utilizing fine growth techniques which provide accurate thickness controllability such as metalorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE) or chemical beam epitaxy (CBE). Such growth techniques may accelerate further development of vertical cavity SE lasers.

In this paper, we will introduce recent progress of vertical cavity surface emitting injection lasers. To begin with, the expected device characteristics of a short cavity SE laser is considered. More specifically, we look at its threshold current, differential quantum efficiency, condition for CW operation, and so on. A superluminescence effect also will be included. Next, we present related fabrication processes and some experimental results on lasing characteristics of CBH SE lasers with GaInAsP/InP and GaAlAs/GaAs systems. Finally, possible improvement for better performances and future prospects will be discussed.

II. Ultimate Performances of Vertical Cavity Surface Emitting Lasers

A. Threshold Current and Quantum Efficiency

The schematic structure of a vertical cavity SE laser is shown in Fig. 1. We consider a circular buried heterostructure, where the active region is buried in a material with smaller band-gap energy and injected carriers are completely confined in the circular active region with diameter D. The optical loss for the resonant mode must balance the gain to reach the threshold, i.e.,

$$g_{th} = \alpha_{ac} + \alpha_{ex}\left(\frac{L}{d} - 1\right) + \frac{1}{d}\ln\frac{1}{\sqrt{R_f R_r}} + \alpha_d \quad (1)$$

where d is the active layer thickness, L is the cavity length, α_{ac}, α_{ex} are the absorption loss in the active and cladding layers, respectively, R_f and R_r are the reflectivities of the front and rear side reflector, and α_d is the diffraction loss. If we assume that $\alpha_{ac} = 10\ \text{cm}^{-1}$, $\alpha_{ex} = 10\ \text{cm}^{-1}$, $\alpha_d = 10\ \text{cm}^{-1}$, $L = 7\ \mu\text{m}$, $d = 3\ \mu\text{m}$, and $g_{th} = 200\ \text{cm}^{-1}$, the necessary average reflectivity must be

$$\sqrt{R_f R_r} = 0.95. \quad (2)$$

The threshold gain is expressed in terms of the threshold carrier density N_{th} as follows:

$$g_{th} = A_0 N_{th} - \alpha_{in} \quad (3)$$

where α_{in} is the residual absorption loss and A_0 is the gain coefficient. The threshold carrier density N_{th} is expressed by

$$N_{th} = \frac{g_{th} + \alpha_{in}}{A_0}. \quad (4)$$

If we put $\alpha_{in} = 400\ \text{cm}^{-1}$ and $A_0 = 3 \times 10^{-16}\ \text{cm}^2$ for the GaAlAs/GaAs system, $N_{th} = 2 \times 10^{18}\ \text{cm}^{-3}$. The threshold current density J_{th} of the SE laser is then expressed as [6]

$$\begin{aligned} J_{th} &= \frac{N_{th}}{\tau_s} \\ &= \frac{edB_{eff}}{A_0^2}\alpha_{ac} + \alpha_{in} - \alpha_{ex} + \frac{L}{d}\alpha_{ex} \\ &\quad + \frac{1}{d}\ln\frac{1}{\sqrt{R_f R_r}} + \alpha_d^2 \end{aligned} \quad (5)$$

where τ_s is carrier lifetime, e is electron charge and B_{eff} is the effective recombination constant. Here we have used the following relationship:

$$\tau_s = \frac{1}{B_{eff} N_{th}}. \quad (6)$$

In the cladding layer of the present device, there is no guiding structure which results in a divergence of a resonant light beam. This may cause a diffraction loss and limits the diameter as a small diffraction loss has to be maintained. Assuming that the transverse field distribution has a Gaussian function with a spot size of s, α_d is given as follows [29]:

$$\alpha_d = \frac{1}{d}\ln\left(\frac{2}{2 + 3(2l_c/ks^2)^2 + (2l_c/ks^2)^4}\right) \quad (7)$$

where l_c is the cladding layer thickness and k is the propagation constant. When we reduce the diameter of active region, which results in decreasing the spot size of a resonant light beam, the diffraction loss α_d increases and begins to dominate.

Fig. 2(a) shows a calculated threshold current density of the GaAlAs/GaAs SE laser against active layer thickness without taking a diffraction loss into account. When $R = 95$ percent and $d = 2$–$3\ \mu\text{m}$, the threshold current density J_{th} is $20 \sim 25\ \text{kA/cm}^2$. This value is the same as that of high radiance LED's and not a surprisingly high level. The similar result is obtained for a GaInAsP/InP SE laser ($\lambda_g = 1.3\ \mu\text{m}$) as shown in Fig. 2(b) [6]. We can find that the threshold current density can be reduced to less than $10\ \text{kA/cm}^2$ by increasing the reflectivity to 99 percent. This may be achievable by employing a suitably-controlled dielectric multilayer reflector. Fig. 3 shows a calculated threshold current density and threshold current against the diameter of the active region in the GaAlAs/GaAs SE laser, where the spot size $2s$ is assumed to be equal to the active region diameter D. When the diameter is more than $3\ \mu\text{m}$, the diffraction loss is negligibly small. Therefore, the threshold current can be decreased proportionally to the square of the diameter in this region. The threshold current takes a minimum in the range of the diameter from 1 to $2\ \mu\text{m}$.

Also, we consider the differential quantum efficiency of the SE laser for the practical use. If we use a nonabsorbing mirror for the front mirror, the differential quantum efficiency from the front mirror is expressed as [19]

$$\eta_d = \eta_i \frac{\ln(1/R_f)}{2\alpha L + \ln(1/R_f R_r)} \quad (8)$$

where η_i is the internal quantum efficiency and α is the internal loss. The calculated result for the GaAlAs/GaAs SE laser is shown in Fig. 4, where a dielectric multilayer reflector and Au coated reflector are considered and we have assumed $R_r = 1.0$ [19]. For simplicity, we have assumed that the internal quantum efficiency $\eta_i = 1$. As for the Au coated mirror, efficiency deteriorates due to the

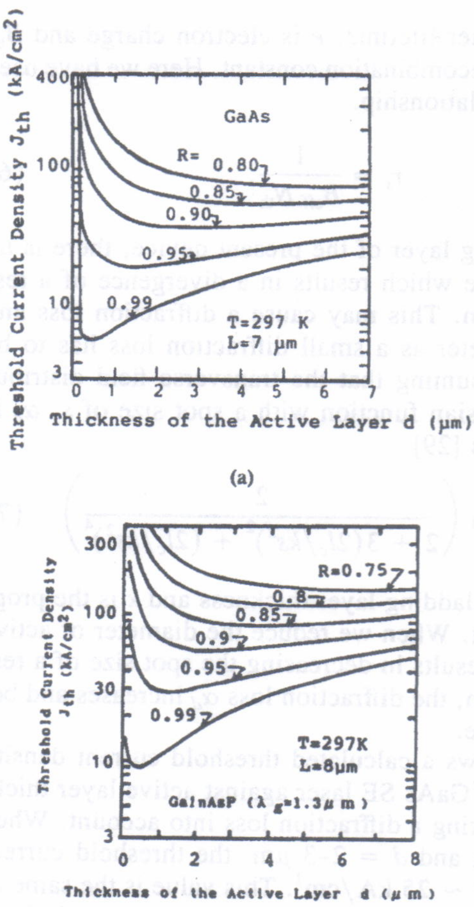


Fig. 2. Threshold current density versus active layer thickness for (a) GaAlAs/GaAs SE laser [19] and (b) GaInAsP/InP SE laser [10].

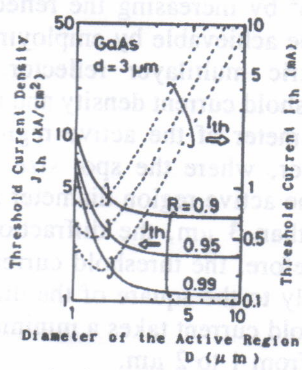


Fig. 3. Threshold current density (solid lines) and threshold current (dashed lines) against active region diameter for GaAlAs/GaAs SE laser.

absorption. In spite of rather high reflectivity of the front mirror (~95 percent), the differential quantum efficiency stays at 60–80 percent because of its short cavity structure.

B. Effect of In-Plane Superluminescence

The emission in the plane of the active layer is enhanced by stimulated emission which may prevent surface emission. When the diameter of the active region is too large, the superradiance of the edge emitting mode might dominate. Therefore, such superluminescence of the edge

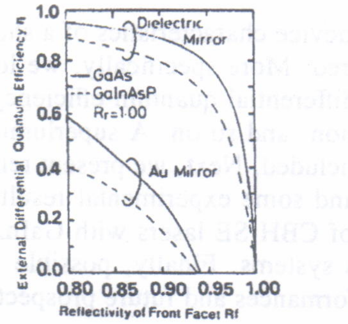


Fig. 4. Differential quantum efficiency versus reflectivity.

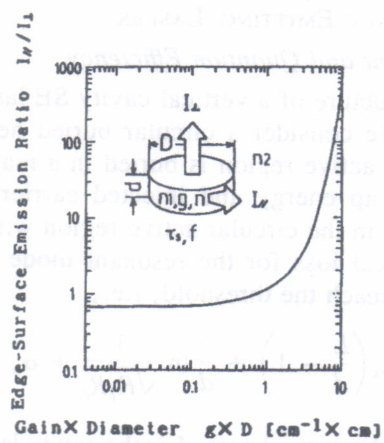


Fig. 5. Ratio of surface and edge emissions taking in-plane superluminescence into account [6].

emitting mode may deteriorate the efficiency of surface emission [30]. Fig. 5 shows a numerical result of the ratio of a surface emission $I_{\perp}$ and edge emission $I_{//}$ against the gain-diameter product for the active region [6], where we have assumed that the gain is uniform over the whole active region. In order to eliminate the unwanted superluminescence of an edge emission, the active region diameter should be less than 20 μm when we assume that the gain is equal to 500 cm^{-1}.

C. Longitudinal Mode Behavior

In a short cavity SE laser, a stable single longitudinal mode oscillation can be expected due to its large mode spacing. Larger mode spacing between main lasing mode and neighboring longitudinal modes will provide a larger gain difference. The mode spacing $\Delta\lambda$ is expressed as

$$\Delta\lambda = \frac{\lambda^2}{2Ln_{\text{eff}}}, \tag{9}$$

where n_{eff} is the effective refractive index. When $L = 7$ μm, $n_{\text{eff}} = 4$, $\Delta\lambda$ is equal to 135 and 460 Å for a GaAs laser ($\lambda = 0.87$ μm) and for a GaInAsP laser ($\lambda = 1.6$ μm), respectively. Gain difference and resultant mode suppression ratio of neighboring modes is evaluated assuming that the gain profile is a parabolic function of wavelength

$$g = AN - B(\lambda - \lambda_0)^2 \tag{10}$$

where we have assumed that the main lasing mode coincides with the gain center λ_0. The suppression ratio of neighboring longitudinal modes is given from a standard multimode rate equation analysis [6] and expressed by

$$P_1/P_0 = \frac{C}{(\Delta g/g_{th})(I/I_{th} - 1)}. \quad (11)$$

Here Δg is the gain difference, g_{th} is the threshold gain, I is the injection current, I_{th} is the threshold current. The parameter C is a spontaneous emission factor [31] given by

$$C = \xi \frac{\lambda}{4\pi^2 n_{eq}^3 \Delta\lambda_s V}. \quad (12)$$

Here n_{eq} and $\Delta\lambda_s$ are the refractive index and the spectral width of the spontaneous emission, respectively, ξ is the optical confinement factor, which is given by d/L in this case, and V is the volume of the active region. When $L = 7$, $d = 3$, and $D = 10$ μm, C is in the order of 10^{-5} for GaInAsP/InP SE lasers ($\lambda_g = 1.6$ μm).

Fig. 6 shows a calculated gain difference and mode suppression ratio as a function of cavity length for GaAlAs/GaAs and GaInAsP/InP ($\lambda = 1.6$ μm) SE lasers. When the cavity length is 10 μm, the gain difference is several tens inverse centimeter, which is comparable to that of well-designed DBR and DFB type dynamic-single-mode lasers [32]. Consequently, the mode suppression ratio of more than 30 dB can be achievable when $I/I_{th} > 1.5$.

D. Thermal Resistance and CW Condition

The threshold current of GaAlAs/GaAs SE lasers has been reduced to around the level of the continuous wave (CW) operation—less than 100 mA. Thus it seems that the CW operation of the GaAlAs/GaAs SE laser can be obtained by well considering the heat dissipation. Fig. 7 shows a model of calculating thermal resistance of an SE laser. The device size dependence of thermal resistance with the thickness of p-cladding layer as a parameter is calculated as shown in Fig. 8 [33]. By reducing the thickness of the p-cladding layer, the thermal resistance R_{th} can be decreased. The increase of the chip size causes the decrease of thermal resistance. The chip size does not have much of an effect on thermal resistance when it is larger than 20 μm. This implies the limit of separation in arrayed lasers. We can easily see five thermal sources in a laser mounted p-side down, i.e., n-cladding, active, p-cladding, cap, and p-contact regions. From a rough estimation, the operating temperature rise ΔT is expressed as

$$\Delta T = R_{th,ac} I E_g/e. \quad (13)$$

Here $R_{th,ac}$ is the thermal resistance of the active region and E_g is the band-gap energy. On the other hand, the temperature dependence of the threshold is expressed as

$$\Delta T = T_0 \ln (I_{th}/I_0). \quad (14)$$

The characteristic temperature T_0 is 150 K for the GaAs material. A CW condition of the SE laser is shown in Fig. 9, when the radius of active region is assumed to be 5 and 3 μm, respectively. The thermal resistance is estimated as 450 K/W when the radius of the active region is made to be 5 μm. Then the CW operation can be obtained at ΔT

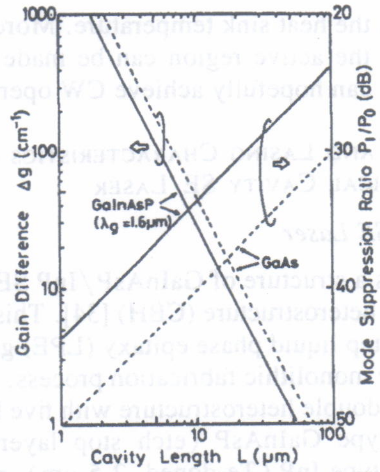


Fig. 6. Gain difference between main mode and neighboring longitudinal mode, and mode suppression ratio against cavity length.

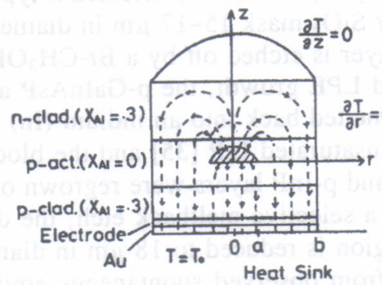


Fig. 7. Calculation model of thermal resistance.

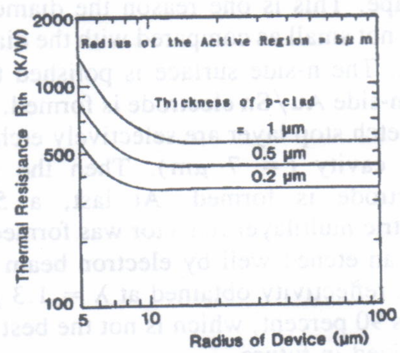


Fig. 8. Thermal resistance of a GaAlAs/GaAs surface emitting laser.

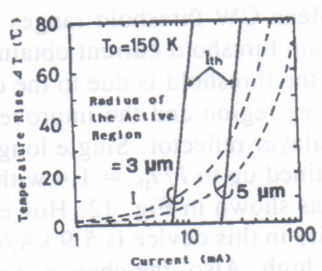


Fig. 9. Temperature rise of active region versus injection current.

= 25 K higher than the heat sink temperature. Moreover, when the radius of the active region can be made to be less than 3 μm, one can hopefully achieve CW operation.

III. Fabrication and Lasing Characteristics of a Vertical Cavity SE Laser

A. GaInAsP/InP SE Laser

Fig. 10 illustrates a structure of GaInAsP/InP SE laser with circular buried heterostructure (CBH) [34]. This laser is grown by a two-step liquid phase epitaxy (LPE) growth and successive fully monolithic fabrication process. In the first LPE growth, a double heterostructure with five layers is grown, i.e., n-type GaInAsP (etch stop layer, Te-doped, 1.5 μm), n-type InP (Te-doped, 2.5 μm), p-type GaInAsP active layer ($\lambda_g = 1.3\ \mu$m, Zn-doped, 2.5 μm), p-type InP (Zn-doped, 1.5 μm), p-type GaInAsP (cap layer, Zn-doped, 0.3 μm) on a (100)-oriented n-type InP substrate. A circular SiO_2 mask 15–17 μm in diameter is formed and p-InP layer is etched off by a Br-CH_3OH solution. In the second LPE growth, the p-GaInAsP active layer is selectively melted back into an indium (In) solution containing an unsaturated InP [35] and the blocking layers, i.e., p-, n-, and p-InP layers were regrown on the etched wafer. After a selective meltback etch, the diameter of the active region is reduced to 18 μm in diameter which is estimated from observed spontaneous emission patterns, although the diameter of side-etched cap layer is 10 μm ϕ. The melted-back mesa is considered to have a circular taper shape. This is one reason the diameter of active region was not small as compared with the diameter of the SiO_2 mask. The n-side surface is polished to 150 μm thick and the n-side Au/Sn electrode is formed. Next, the substrate and etch stop layer are selectively etched off to form a short cavity ($\simeq 7\ \mu$m). Then the p-side Au/Zn/Au electrode is formed. At last, a 5 pair SiO_2/TiO_2 dielectric multilayer reflector was formed only on the bottom of an etched well by electron beam evaporation. The peak reflectivity obtained at $\lambda = 1.3\ \mu$m of the multilayer was 90 percent, which is not the best value and will be optimized in future.

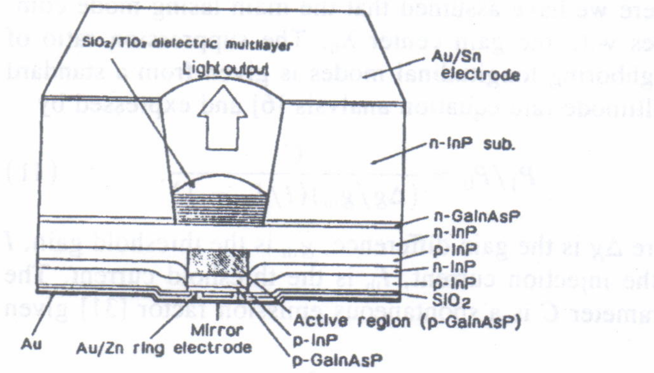


Fig. 10. Schematic view of a circular buried heterostructure (CBH) GaInAsP/InP surface emitting laser [34].

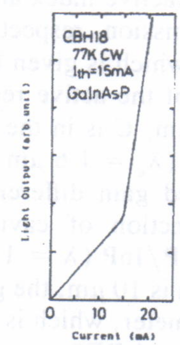


Fig. 11. Current–light output characteristic of a GaInAsP/InP SE laser at 77 K under CW conditions [34].

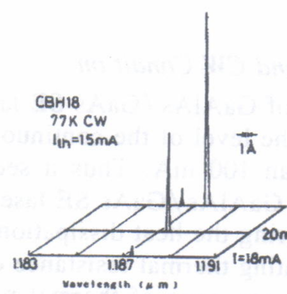


Fig. 12. Lasing spectra of a GaInAsP/InP SE laser at 77 K under CW conditions [34].

Fig. 11 shows the current–light output (I–L) characteristic of one of the CBH SE laser devices at 77 K under a CW condition [34]. Mean CW threshold ranges from 15 to 35 mA. The minimum threshold current obtained is 15 mA. The reduction of the threshold is due to the decrease of the diameter of active region and the improvement of the reflectivity in multilayer reflector. Single longitudinal mode operation is obtained up to $I/I_{th} = 1.4$ without any subtransverse modes, as shown in Fig. 12. However, the threshold current density in this device is 5.9 kA/cm^2 and this level is still rather high. Also, the characteristic temperature of T_0 of the threshold current was worse than that of a round-low-mesa structure device [11] with optimized Au/SiO_2 mirrors. The characteristic temperature T_0 was 85–95 K for low temperature region and 30–40 K for high temperature region, respectively, with the turning point of 180 K. Such a low T_0 limits the operating temperature up to 200 K. This may be because the reflectivity of mirrors is insufficient due to the fluctuation of layer thickness in a fabricated dielectric multilayer. Also, there is supposed to exist some leakage of current near the boundary of the active and blocking region, or through the blocking region. It is expected that the threshold current could be much lower and room temperature oscillation will be possible by some improvement such as by optimizing the layer thickness and doping level of blocking region, by introducing a suitably-controlled dielectric multilayer mirror with higher reflectivity for the n-side reflector, and by reducing the diameter of active region.

B. LPE Grown GaAlAs/GaAs SE Laser

Fabricated GaAlAs/GaAs laser devices employ almost the same CBH structure as the GaInAsP/InP laser, as shown in Fig. 13. In order to decrease the threshold, the

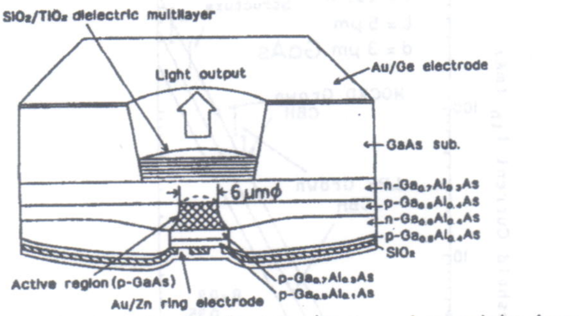


Fig. 13. Schematic view of a CBH GaAlAs/GaAs surface emitting laser [18].

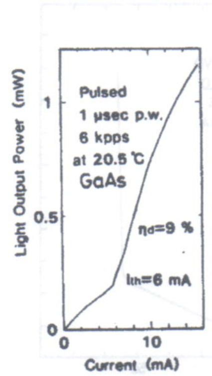


Fig. 14. Current-light output characteristic of a GaAlAs/GaAs SE laser under room temperature pulsed operation [18].

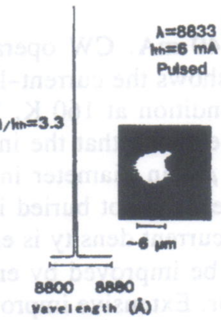


Fig. 15. Lasing spectrum and near-field pattern of a GaAlAs/GaAs CBH surface emitting laser [18].

active region is also constricted by the selective meltback method mentioned above [36]. The minimum threshold current of 68 mA was obtained under pulsed operation when the active region was constricted to 14 μm in diameter [17]. Moreover, the threshold is reduced to 6 mA when the diameter is ~ 6 μm under pulsed operation at 20.5°C [18]. Fig. 14 shows the current–light output characteristic under room temperature pulsed operation. The threshold current density in this case is 21 kA/cm^2, which agrees with the theoretical value when we postulate the reflectivity of 95 percent. Fig. 15 illustrates a lasing spectrum at I = 20 mA and the near-field pattern. This SE laser device operates in a single mode but the linewidth is broadened when the current I exceeds 40 mA. The near-field pattern of this SE laser is a circle of $D \cong 6$ μm in diameter. CW operation is also obtained with I_{th} = 4.5 mA (77 K), which is the first CW demonstration of a vertical GaAlAs/GaAs surface emitting (SE) laser. It is noted that a microcavity which is 7 μm long and 6 μm in diameter has been realized. From this demonstration of a microcavity SE laser, we find that an extremely low threshold current operation with stable single transverse mode is expected by decreasing the diameter.

C. *MOCVD Grown GaAlAs/GaAs SE Laser*

We have been fabricating SE lasers mostly by liquid phase epitaxy (LPE), where the resulting surface morphology is not satisfactory in our experiment. In order to improve the surface morphology, which is more important for SE lasers than for conventional stripe lasers, we introduced an metalorganic chemical vapor deposition (MOCVD) growth for SE lasers [37]. The crystal quality of MOCVD grown wafers for the purpose of fabricating SE lasers is found to be comparable or somewhat superior to those grown by LPE. Fig. 16 shows a schematic view of an MOCVD grown CBH SE laser [38]. This laser structure is realized by a two-step MOCVD growth and fully monolithic technology. First, a GaAlAs/GaAs DH wafer with the active layer thickness of 3 μm is grown by MOCVD at the temperature of 780°C under atmospheric pressure. After the first growth, a silicon nitride (Si_3N_4) circular mask with a diameter of 10 μm is formed on the wafer for mesa etch and selective regrowth of current blocking layers. A p-cladding GaAlAs layer is lightly etched by a sulphuric acid (H_2SO_4):H_2O: hydrogen peroxide (H_2O_2) = (1:8:8) solution. Selective MOCVD regrowth of GaAs under atmospheric pressure is employed to form current blocking layers (0.7 μm thick n-GaAs and 0.3 μm thick p-GaAs). The growth condition is the same as that used in the double heterostructure (DH) wafer growth. There is no deposition on the top of a circular mesa which has been protected with a Si_3N_4 mask. The short cavity structure with the cavity length of 6 μm is formed by removing a GaAs substrate. A ring electrode with outer/inner diameter of 40/10 μm is adopted and a Au/SiN mirror is prepared as an n-side mirror in this experiment for a rapid characterization.

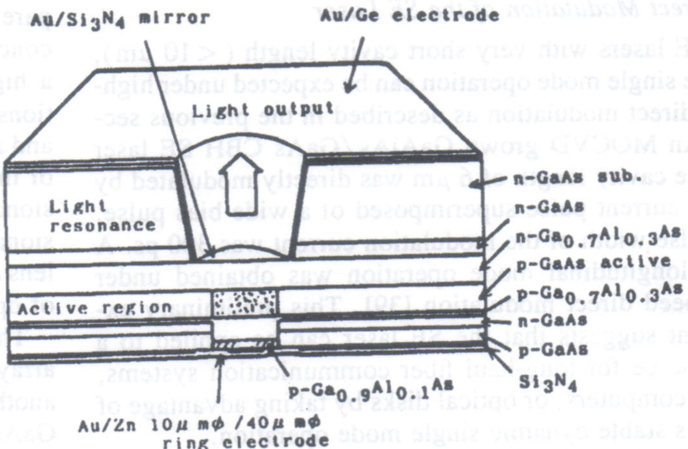


Fig. 16. Schematic view of an MOCVD grown CBH GaAlAs/GaAs SE laser [38].

Threshold currents of these fabricated devices under room temperature pulsed condition range from 40 to 100

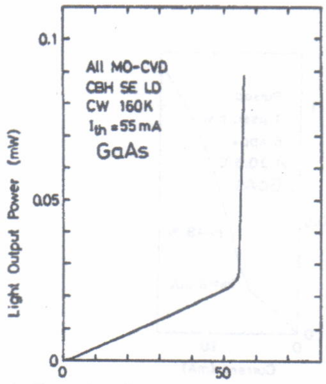


Fig. 17. Current-light output characteristic of an MOCVD grown CBH GaAlAs/GaAs SE laser under CW conditions at 160 K.

mA with the minimum of 40 mA. CW operation up to 230 K is obtained. Fig. 17 shows the current-light output characteristic under CW condition at 160 K. From measured near-field patterns, we found that the injected current spreads in a circle 13 μm in diameter in the active region, since the active layer was not buried in blocking layers. Thus, the threshold current density is estimated to be 30 kA/cm^2, which may be improved by employing a dielectric multilayer reflector. Extensive improvements of SE lasers can be expected by employing a well-controlled MOCVD growth.

D. Direct Modulation of the SE Laser

In SE lasers with very short cavity length (<10 μm), a stable single mode operation can be expected under high-speed direct modulation as described in the previous section. An MOCVD grown GaAlAs/GaAs CBH SE laser with the cavity length of 6 μm was directly modulated by a short current pulse superimposed of a wide bias pulse. The pulse width of the modulation current was 300 ps. A single longitudinal mode operation was obtained under high-speed direct modulation [39]. This preliminary experiment suggests that the SE laser can be applied to a light source for long-haul fiber communication systems, optical computers, or optical disks by taking advantage of the SE's stable dynamic single mode operation.

IV. Future Prospects

A. Extremely Low Threshold SE Laser

Fig. 18 shows the relationship between the threshold and the active region diameter in GaAlAs/GaAs CBH SE lasers. When the diameter of the active region is large enough to maintain a small diffraction loss, I_{th} is proportional to the square of the diameter of the active region. However, the threshold meets a minimum when we reduce the diameter since the diffraction loss begins to dominate. Experimental data are plotted in Fig. 18. We find that the diffraction loss is negligibly small for $D > 3$ μm. An ultralow threshold device with less than 1 mA is expected by decreasing the diameter to be less than 2–3 μm.

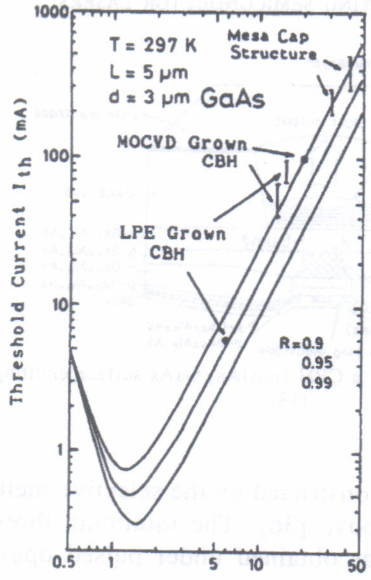


Fig. 18. Threshold current against diameter of active region for a GaAlAs/GaAs SE laser.

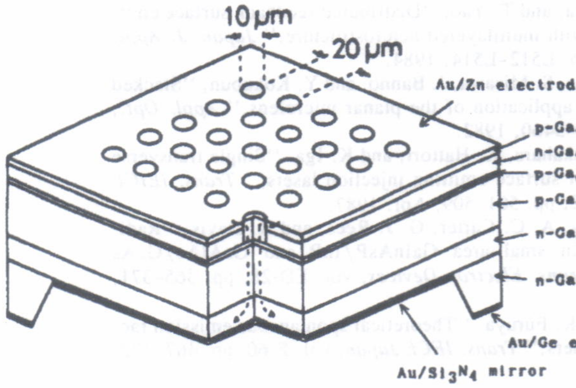
B. Two-Dimensional SE Laser Array

A conventional injection laser consists of two cleaved end mirrors perpendicular to the active layer, so that only one-dimensional laser arrays can be monolithically fabricated, otherwise wafers must be stacked to form a two-dimensional laser array. However, it is possible to prepare a two-dimensional laser array by using an SE laser concept. Specifically, a vertical cavity SE laser can form a high-density two-dimensional arrays. One of applications of those two-dimensional arrays is a high-power laser and another is the stacked planar optics [28]. The concept of the stacked planar optics is to construct a two-dimensional lightwave component array by stacking two-dimensional planar optical device arrays with the planar microlens array. This configuration may enable mass production of optical devices with easy alignment.

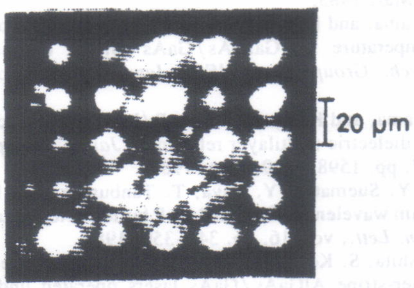
The first demonstration of a two-dimensional SE laser array was performed with the GaInAsP system [40]. As another preliminary demonstration, a 5 × 5 GaAlAs/GaAs SE laser array was fabricated by a two-step MOCVD growth, as shown in Fig. 19(a). The separation of each device was 20 μm, where the current confining structure was the same as mentioned previously. This device operated under a room temperature pulsed condition with a threshold of 600 mA. Thus, the minimum threshold in 25 SE LD's is estimated to be 24 mA. Fig. 19(b) shows near-field patterns with bias current of 2.2 times the threshold. The lasing operation of 19 SE LD's among 25 devices was obtained. Such a high density 2-D laser array can be formed only by a vertical cavity configuration.

C. Semiconductor Multilayer Structure

The MOCVD as well as chemical beam epitaxy (CBE) can easily provide superlattice structures, which enable DFB type and DBR type SE lasers [9]. For the purpose



(a)



(b)

Fig. 19. 2-dimensional surface emitting laser array. (a) Schematic diagram. (b) Near-field pattern of a 5 × 5 GaAlAs/GaAs SE laser array.

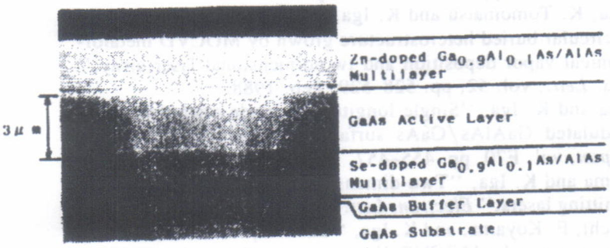


Fig. 20. A cross-sectional SEM photograph of a wafer with $Ga_{0.9}Al_{0.1}As/AlAs$ multilayer Bragg reflector.

of realizing DBR SE lasers, a DH wafer with a 3 μm thick GaAs active layer sandwiched by a couple of 15 pair $Ga_{0.9}Al_{0.1}As/AlAs$ Bragg reflectors was grown by the aforementioned MOCVD technique. A cross-sectional scanning electron microscope (SEM) photograph of the active layer sandwiched by the multilayers is shown in Fig. 20. The period of the Bragg reflector was 1400 Å. The reflectivity of the multilayer Bragg reflector was measured from the top of the crystal surface. The maximum reflectivity of 97 percent was obtained at a wavelength of 0.87 μm as shown in Fig. 21, which corresponds to the lasing wavelength of the GaAlAs/GaAs SE laser. Also, we found that it is possible to inject the carrier into an active region through multilayers by appropriately doping the impurity. Recently we succeeded in the oscillation of a GaAlAs surface emitting laser which uses a multilayer reflector for one of the mirrors [41].

By introducing such a periodic configuration, a reduction of the threshold current can be expected [42]. To fully activate a multilayered active region such as a multi-quantum well (MQW) and DFB, we also proposed a transverse or interdigital injection scheme [43]. A DBR or DFB structure without facet mirrors enables the integration of functional optical devices with SE lasers by stacking them. This may open up a new three-dimensional integrated optics.

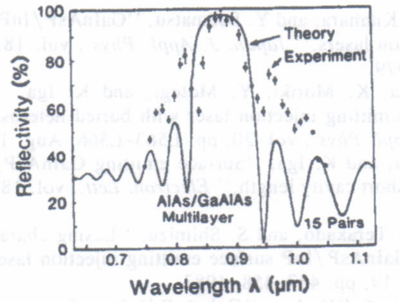


Fig. 21. Measured spectral reflectivity of a 15 pair $Ga_{0.9}Al_{0.1}As/AlAs$ multilayer in comparison with the theory.

V. Conclusion

A vertical cavity SE laser contains many advantages which are proper to its novel structure, i.e. not only mass-productivity and the possibility of forming a two-dimensional laser array, but also its excellent laser performance. For example, stable dynamic-single-mode operation and an extremely low threshold ($I_{th} < 1$ mA) can be expected by introducing a microcavity structure with a cavity length and an active region diameter of several microns. In order to reduce the threshold current of SE lasers, we introduced a circular buried heterostructure (CBH) and improved the laser reflectors by employing a dielectric multilayer reflector. With the progress of our SE laser research up to now, it is clear that the present performances of vertical cavity SE lasers are not limited by any essential problem, but only by technical ones. By overcoming those technical problems such as ohmic resistivity in the electrode and bonding on heat sink without deterioration of the mirrors, we may obtain room temperature CW operation of the SE laser in the near future.

Detailed lasing characteristics of SE lasers such as transverse mode behavior, including polarization state, feedback noise, and spectral linewidth, are still open to investigation. Further development of the SE laser may open up various applications and accelerate the integration of optical devices and optical circuits with the freedom of the two-dimensional array.

Acknowledgment

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