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Vertical Cavity Surface Emitting Lasers —Device Technology and Future Prospects—

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Research progress of vertical cavity surface emitting (SE) lasers is reviewed. State-of-the-art laser performances, expected laser characteristics, and future prospects are described. A densely packed two-dimensional lasers array is demonstrated for parallel optical processing and high-power applications. Basic technologies, such as low damage micro-fabrication and growth of ultra-thin layers, have been developed for advanced SE lasers.

1. Introduction

The surface emitting (SE) lasers [1] is rapidly attracting a current research looking forward to new parallel optical technologies. In particular, a vertical cavity SE laser exhibits many preferable laser characteristics, such as ultra-low threshold, single mode operation, narrow circular beam, etc.. These indicate very important features for various applications, such as high-capacity optical fiber communications, laser disk memories and optical interconnection in LSI's.

The authors proposed a vertical cavity SE laser in 1977, and research efforts to make it real has been made [1]. In order to reduce the threshold current, we performed several improvements in laser reflectors and introduced a circular buried heterostructure for effective current confinement [2]. The first room temperature cw operation of a vertical cavity SE laser was achieved in 1988 [3]. After we demonstrated good lasing characteristics of SE lasers, much attention has been paid for SE lasers and many research groups started the vertical-cavity SE laser research. Recently, extremely low threshold devices lower than 1mA began to be reported [4],[5].

In this paper, we review the recent progress of the vertical cavity SE laser, and describe its expected device characteristics. Ultimate performances of a microcavity SE laser including basic fabrication technologies for advanced SE lasers will be discussed.

2. Laser Performances

(a) CW Lasing Characteristics

We demonstrated a GaAlAs/GaAs microcavity SE laser as shown in Fig. 1. This laser was fabricated by a two step MOCVD growth and processed by a fully monolithic technology. A short cavity of 5.5μm long was formed by chemically removing the GaAs substrate. Figure 2 shows a typical current/light output characteristic and lasing spectrum under cw condition at 20 ℃. The maximum cw output power was 2.2 mW. We believe this could be raised up to several mW or more by improving heatsinking. Stable single mode operation was observed. Single mode operation of these SE lasers originates from its large longitudinal mode spacing of 200Å. The side mode suppression ratio of 35 dB was obtained. This is comparable as that of well-designed DBR or DFB dynamic single mode lasers.

The spectral linewidth was measured by a delayed self-homodyne method [6]. The linewidth of 50 MHz was obtained at the output power of 1.4 mW. We expect that much narrower linewidth is obtained by increasing the output power and reducing the cavity loss.

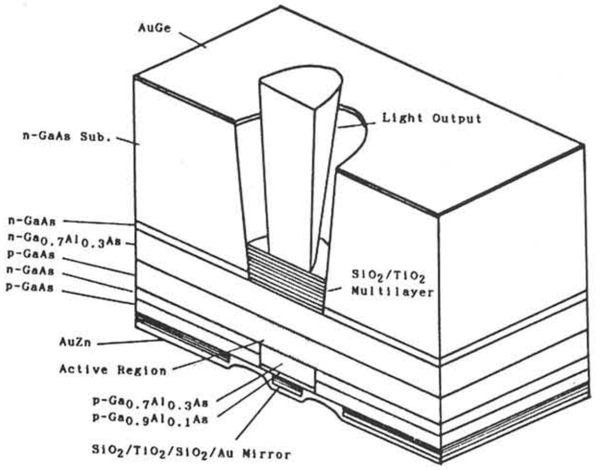

Fig. 1 GaAlAs/GaAs vertical cavity surface emitting laser.

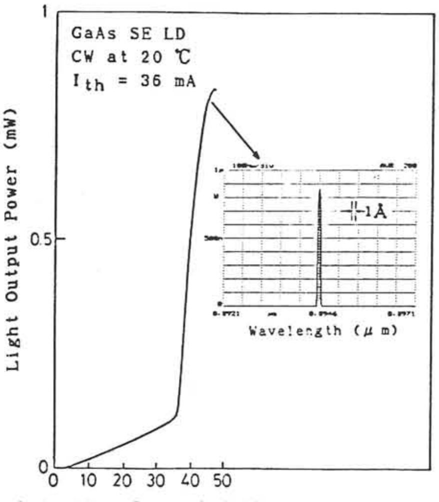

Fig.2 Light output/current characteristic and lasing spectrum.

(b) Low Threshold Devices with Multilayer Structure

An SE laser with a quantum well active region is expected to provide not only a higher gain but also better performances. We reported for the first time a laser oscillation of an MQW SE laser by current injection [7]. If the reflectivity is increased to 99.9%, a single QW can be used and very low threshold current density is expected.

Semiconductor multilayer reflector provides high reflectivity of more than 99%. We demonstrated the first pulsed operation GaAlAs/AlAs DBR SE injection laser [7]. Jewell et al. demonstrated 1.2mA threshold device with DBR and strained GaInAs QW structure [4]. Moreover, the threshold was reduced to 0.7 mA [5]. Also, large differential quantum efficiency of 78% was demonstrated [8]. Table I summarizes some laser performances of existing vertical cavity SE lasers.

	GaInAsP	GaAlAs	InGaAs
I_{th}	6mA(77K)(Tokyo IT) 5mA(77K)(AT&T) 150mA(300K)(Furukawa)	5.2mA(Sanyo) 2.2mA(AT&T)	0.8mA(AT&T) 0.7mA(UCSB)
J_{th}		10kA/cm^2(TRW) 1.4kA/cm^2(AT&T)	1kA/cm^2(Bellcore) 600A/cm^2(UCSB)
η_d	*	14%(Tokyo IT) 78%(AT&T)	28%(AT&T)
$\Delta\nu$	<1Å(Tokyo IT)	50MHz(Tokyo IT)	85MHz(UCSB)
$\Delta\nu \cdot P$	*	89MHz · mW(Tokyo IT)	5MHz · mW(UCSB)
RIN	*	<-140dB/Hz(Tokyo IT)	
P_{out}(cw)		3.2mW(AT&T)	0.6mW(AT&T)
P_{out}(Pulse)	2mW (77K) (Tokyo IT) 3mW(300K) (Furukawa)	120mW(TRW)	18mW(AT&T)
f_m	*	300ps pulse(Tokyo IT)	8GHz (AT&T)

Table I Summary of SE laser performances.

3. Perspective of Ultra-low Threshold Microcavity SE Laser

Although the threshold is reaching a half-milliamps range, it is still higher than the theoretical value. This is due to nonradiative recombination at the side wall of the active region. Figure 3 shows the calculated threshold for a microcavity SE laser with a cylindrical waveguide. The core/cladding index difference was assumed to be 5%. An ultra-low threshold with a few μA is expected by decreasing the diameter to be less than 1 μm. Experimental data of present devices are also plotted in Fig. 3. The realization of these μA threshold SE lasers is a target in the future research.

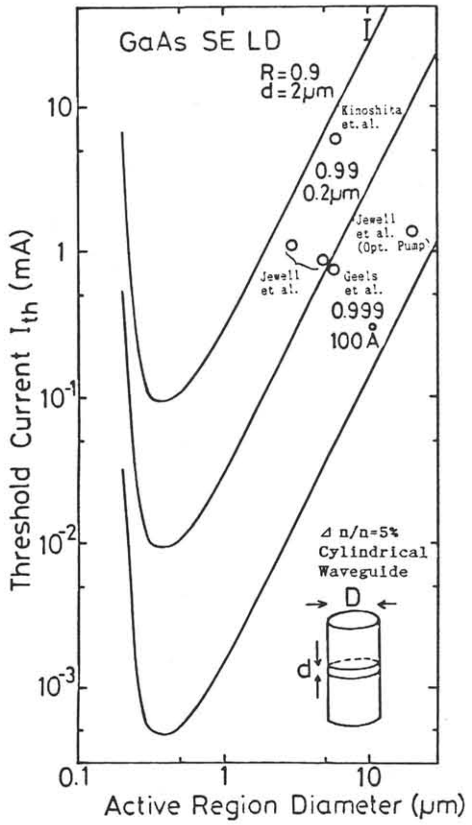

Fig. 3 Threshold of microcavity SE laser.

4. Basic Technologies for Advanced Microcavity SE Laser

(a) Low Damage Micro-fabrication

In order to realize micron-order or submicron laser devices, the development of micro-fabrication tools must be established. A fine and low damage etching condition by ultra-high vacuum background RIBE using Cl_2 gas has been made clear [9]. Figure 4 shows an SEM photograph of a micro-mesa structure formed by RIBE. The damage can be relaxed by choosing the appropriate condition of acceleration voltage and substrate temperature. We found the vertical wall and good mask traceability condition is that the acceleration voltage is 200V and substrate temperature is 150℃. Residual damage are characterized by photoluminescence and making stripe lasers.

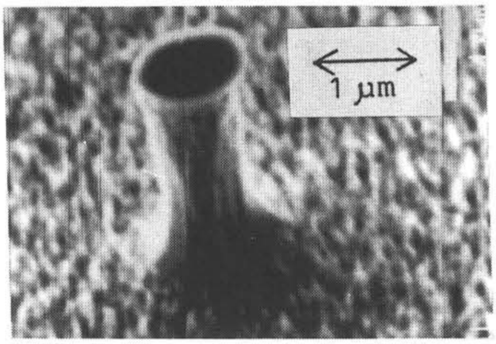

Fig. 4 SEM photograph of a InP circular mesa formed by RIBE.

(b) Chemical Beam Epitaxy for SE Laser

In order to explore ultimate performances of vertical cavity SE laser, a finer growth technology with accurate thickness control and good surface morphorogy is needed. We have developed chemical beam epitaxy (CBE) for GaInAsP/InP surface emitters [10]. We expect this growth technology can easily provide super-lattice structures, that enable DBR-type SE lasers. A cross-sectional SEM photograph of the GaInAs/InP multilayer Bragg reflector grown by CBE are shown in Fig. 5. Also, the QW structure with several atomic layers including strained QW are now under investigation [11].

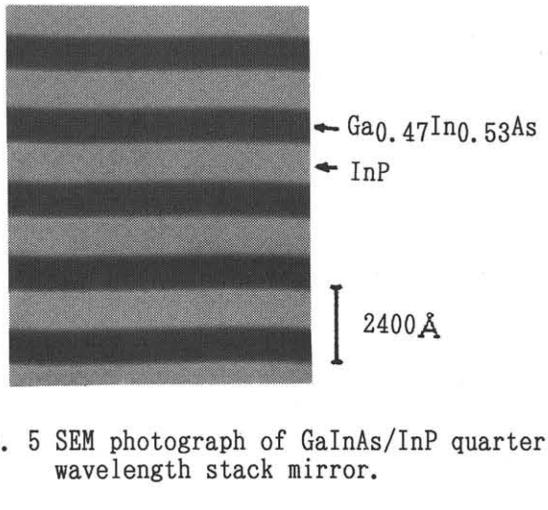

Fig. 5 SEM photograph of GaInAs/InP quarter wavelength stack mirror.

5. Two-dimensional Array and Stacked Photonic Integration

The vertical cavity SE laser can form a densely packed 2-D array. One of applications of those 2-D arrays is a high power laser and another is the stacked planar optics [12]. The concept of the stacked planar optics is to construct a 2-D lightwave component array by stacking 2-D planar, optical device arrays with the planar microlens array. This configuration may enable mass production of optical devices with easy alignment. The importance of 2-D array has been increasing along with the development of optical parallel processing.

Figure 6 shows a schematic 2-D array and its near field pattern. The maximum output power was 80 mW under pulsed condition. Higher power operation can be expected by making a large scale array. A phase-locked 2-D array is attractive for high-power and narrow circular beam operation. Appropriate design of phase-locked 2-D laser arrays using diffraction coupling provides a stable operation [13],[14]. The super-mode control in phase locked SE laser array is now under study.

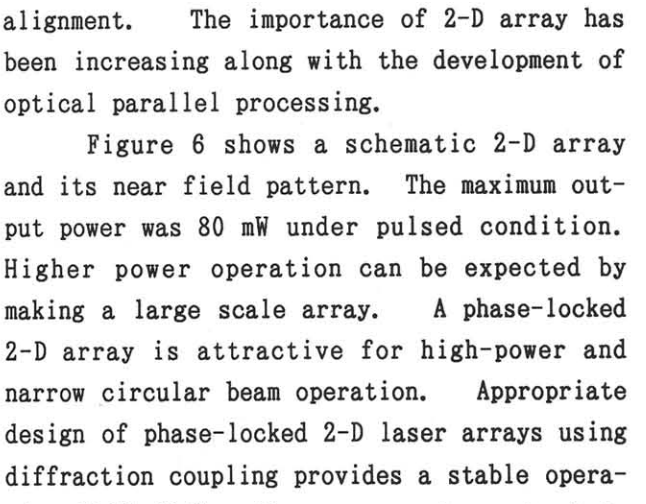

Fig. 6 Schematic 5×4 two-dimensional array and near field pattern.

6. Conclusion

A vertical-cavity SE laser contains a lot of advantages, which include not only mass productivity and 2-D array formation, but also excellent laser performances. For example, an ultra-low threshold ($I_{th} < 1$mA) can be expected by introducing a micro-cavity structure. The SE laser should be considered not as a laser but as a kind of Ⅲ-V compound integrated circuit. The exploitation of necessary semiconductor technologies, such as damage-free micro-fabrication process, atomic layer epitaxy, and micro-heat-sinking, may accelerate the research progress of the SE laser.

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References

[1] K. Iga, F. Koyama and S. Kinoshita, IEEE J. Quantum Electron., 24, pp.1845-1853, 1988.
[2] K. Iga, S. Kinoshita and F. Koyama, Electron. Lett., 23, pp.134-136, 1987.
[3] F. Koyama, S. Kinoshita and K. Iga, Opto-Electronics Conference (OEC'88), Tokyo, Post Deadline Paper, PD-4, October 1988.
[4] J.L. Jewell, A. Scherer, S.L. McCall, Y.H. Lee, S.J. Walker, J.P. Harbison, and L.T.Florez, Electron. Lett., 25, 1123, 1989.
[5] R.S. Geels and L.A. Coldren, DRC'90, ⅧA-1, 1990.
[6] M. Tanobe, F.Koyama and K. Iga, Electron. Lett., 25, 1444, 1989.
[7] T. Sakaguchi, F. Koyama and K. Iga, Electron. Lett. 24, 928, 1988.
[8] H.J. Yoo, J.R. Hayes, N. Andreadakis, E.G. Paek, G.K. Chang, J.P. Harbison and L.T. Florez, Y.S. Kwon, DRC'90, ⅧA-2, 1990.
[9] T. Tadokoro, F. Koyama and K. Iga, J. Vac. Sci. Technol., B7, 1111, 1989.
[10] T.K. Uchida, T. Uchida, K. Mise, F. Koyama and K. Iga, Jpn. J. Appl. Phys., 29, 562, 1990.
[11] T.K. Uchida, T. Uchida, N. Yokouchi, K. Mise, F. Koyama and K. Iga, to be presented at SSDM'90.
[12] K. Iga, M. Oikawa, S. Misawa, J. Banno and Y. Kokubun, Appl. Opt. 21, 3456, 1982.
[13] J.R. Leger, M.L. Scott, W.B. Veldkamp, Appl. Phys. Lett., 52, 1771, 1988.
[14] E. Ho, F. Koyama and K. Iga, Proc. of MOC/GRIN'89, H5, 228, 1989.