Japanese Journal of Applied Physics

The Japan Society of Applied Physics

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Japanese Journal of Applied Physics
Vol. 47, No. 1, 2008, pp. 1–10

Invited Review Paper

Pioneering Contributions to Applied Physics in the Last Half Century

Vertical-Cavity Surface-Emitting Laser: Its Conception and Evolution

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(Received June 11, 2007; accepted July 3, 2007; published online January 18, 2008)

The vertical-cavity surface-emitting laser (VCSEL) is becoming a key device in high-speed optical local-area networks (LANs) and even wide-area networks (WANs). This device is also enabling ultraparallel data transfer in equipment and computer systems. In this paper, we will review its physics and the progress of technology covering the spectral band from the infrared to the ultraviolet, by featuring materials, fabrication technology, and performances such as threshold, output power, polarization, modulation and reliability. Lastly, we will touch on its future prospects. [DOI: 10.1143/JJAP.47.1]

KEYWORDS: surface-emitting laser, vertical-cavity surface-emitting laser, VCSEL, distributed Bragg reflector, DBR, semiconductor laser, gigabit ethernet, LAN, quantum well, microlens

1. Introduction

The vertical-cavity surface-emitting laser (VCSEL) shown in Fig. 1 is a relatively new class of semiconductor laser that is monolithically fabricated.[1–3] It is now considered to be an important device for the gigabit Ethernet, high-speed local-area networks (LANs), computer links, and optical interconnects. In this paper, we review the technical progress of VCSEL devices in the spectral range from the infrared to the ultraviolet by featuring the physics, materials, fabrication technology, and performances such as threshold, output power, polarization, modulation, tenability and reliability. Then, we will discuss some emerging applications.

Since 1992, VCSELs based on the GaAs substrate have been extensively studied and some 980, 850, and 780 nm devices have been commercialized into various lightwave systems. With the aim of exploring applications, 1300–1550 nm long-wavelength, red AlGaInP, and blue–ultraviolet GaN devices are now being developed.

2. Conception of Vertical-Cavity Surface-Emitting Laser

Around 1976, the transmission loss of an optical fiber was predicted gradually to become small for wavelengths longer than 1 µm.[4] However, no semiconductor laser operable in this wavelength band existed then. At the time, it began to be realized that a laser of the GaInAsP semiconductor system could be operated with such long wavelengths. At some institutions including that of the author's group, the data of room-temperature operation at 1300 nm wavelength also began to be reported. Dissatisfaction was felt with the laser until then, and the author was investigating the crystal growth of GaInAsP/InP and devices at around 1977, because almost all semiconductor lasers were being fabricated by cleaving crystals.

One means of forming a laser resonator is to used a distributed feedback (DFB) laser, since this laser is obtained using a diffraction grating without cleavage. (The output end of the laser requires cleaving to obtain a precision surface.) Another way is to make the Fabry–Perot resonator by etching, whereby lasers can be manufactured without cleavage. However, the author desired a newer idea. (The author was with Bell Laboratories for one year and a half from 1979, and mainly conducting the investigations of these subjects).

Fig. 1. Sketch of VCSEL conceived in 1977.

After pondering the idea, the author had a brainstorm on March 22 of 1977 and come up with the concept of the surface-emitting laser shown Fig. 1.[5]

An investigation on realizing the idea began immediately after its conception. The initial proposal was made by the author at a conference in March 1978.[6] The first report of device realization appeared in 1979.[7] The device was driven by a pulse at liquid-nitrogen temperature. The threshold was 800 mA, but the device was quickly damaged. High-intensity light was emitted from the device at a certain current level with a narrow spectrum; this was clearly laser oscillation. The "surface-emitting laser" was named and by Professor Yasuharu Suematsu. It is often called vertical-cavity surface-emitting laser (VCSEL) to distinguish it from other types of surface-emitting lasers, such as the second-order grating type and 45 mirror type which appear later on.[3]

The author was not necessarily confident of the realization of the surface-emitting laser from the beginning. The estimated conditions of laser oscillation were very critical; the possibility of realization was 50%. A newly born novel idea is dangerous, since it might make students prisoners of laboratory entering into its research. The author considered it important to clarify whether it is difficult on an axiom, or a technically solvable problem. This kind of clarification should be the role of university professors.

In 1980, the author returned from Bell Laboratories after a term of one year and a half, and began concentrated research

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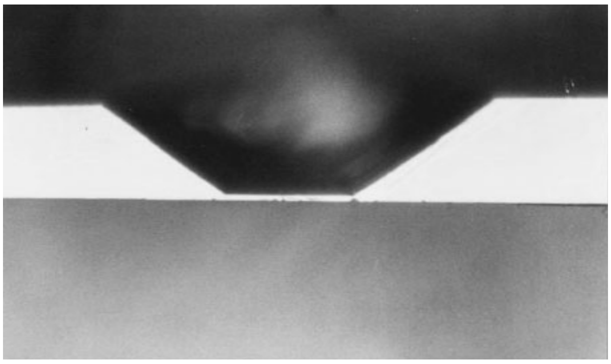

Fig. 2. Etched thin film of InP–GaInAsP–InP double heterostructure for VCSEL (in the middle).

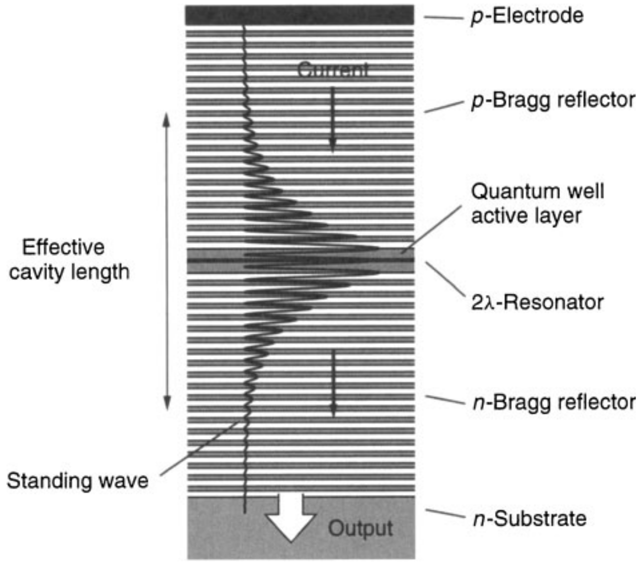

Fig. 3. Structure and field distribution of distributed Bragg reflector for VCSEL (after T. Baba, unpublished).

on the surface-emitting laser. It was found that it is useful to employ a short cavity structure, as shown in Fig. 2, with a thickness of about 6 μm, to render the threshold current small.[8)] Such a device exhibited surface-emitting laser performance with a low threshold even at low temperature. The author considered laser oscillation to be verified by this experiment. (The paper or this experiment, which was presented at the 1982 Solid State Device and Materials Conference sponsored by the Japan Society of Applied Physics,[9)] was bestowed the SSDM Award in 2006 after 24 years.) However, the GaInAsP system includes a relatively high optical loss due to free-carrier absorption and non-radiative recombination. Therefore, continuous wave operation was not achieved until far later in 1994.

The author also began research on the surface-emitting laser using a GaAs system from around 1984. There was an atmosphere of the semiconductor laser research at long wavelengths being the major target in the technical community at the time, and there was already little use for short wavelength lasers. The appearance of the compact disc (CD) reversed this trend again.

Although the surface-emitting laser of short-wavelength bands was born in such a background, the author was able to demonstrate the threshold of 6 mA with pulsed operation in 1986.[10)] The device with a threshold of 1/10 or less that of the conventional semiconductor laser was achieved by adopting the buried structure. The threshold current density was 20 kA/cm^2. Its size was 7 μm in length and 6 μm in diameter. In this way, the laser of micron order became possible for the first time.

Then, Fumio Koyama (presently, professor at Tokyo Institute of Technology), Kinoshita, and myself succeeded in the continuous operation of the surface-emitting laser of a GaAs system at room temperature for the first time in 1988.[11)] The detailed operating characteristics of the surface-emitting laser were clarified,[12)] and devices having threshold current of 20–30 mA, external differential quantum efficiency of about 10–20%, and laser output of about 1–2 mW were obtained. Stable single-wavelength operation was simultaneously confirmed and it was considered to be a dynamic single-mode laser. Namely, the longitudinal-mode interval was 17 nm and the side-mode suppression ratio (SMSR) was 35 dB at $I/I_{th} = 1.25$. The device which is not shameful as a friend of laser was realized for the first time in 1988. An evaluation parameter called the side-mode suppression ratio (SMSR) was defined by Professor Yasuharu Suematsu and Shigehisa Arai (presently, Professor at Tokyo Institute of Technology) to show the merit of the single-mode laser. Now, it is accepted as an international standard from Japan.[4)]

The author also considered the use of semiconductors as reflectors; if two different semiconductors are stacked by turns by 1/4 wave of thickness, light will be strongly reflected by the interference manner as shown in Fig. 3.[13)]

Using the surface-emitting laser with this kind of reflector, a laser resonator can be made by crystal growth, and optoelectronic devices, such as an optical switch, can be stacked onto a surface-emitting laser. This method was attempted by the authors and co-workers adopting liquid phase epitaxy from around 1984. The first surface-emitting laser of GaAs/AlAs multilayer films was made by metal–organic chemical vapor deposition (MOCVD) in 1986.[14)] It took sometime to complete the MOCVD reactor, since we had designed and manufactured the machine by ourselves. In 1986, very flat and high-quality semiconductor films were grown. The author also performed a trial in which a quantum well was used as an active layer.

J. L. Jewell (presently with Pico Light Inc.) and co-workers at AT & T Bell Labs fabricated a surface-emitting laser having a strained quantum well (8 nm, $Ga_{0.8}In_{0.2}As$) in 1989, and realized room-temperature continuous operation by optical pumping. Prior to this, Jewell visited the author's laboratory and discussed on the surface emitting lasers that were demonstrated in 1988. Current injection devices were demonstrated by his group in 1989.[15)] Subsequently, the research consortium of Bell Labs and Bellcore fabricated a microresonator with a diameter of 2–3 μm and an active-layer thickness of 8 nm, and realized the oscillation threshold of 1–2 mA.

Moreover, Randy Geels and Larry Coldren at the University of California Santa Barbara realized continuous oscillation with the threshold of 0.7 mA.[16)] With the structure which embeds a minute circular mesa with polyimide. Karl J. Ebeling and colleagues of Ulm University attained a threshold of 0.65 mA using a device fabricated by MBE in 1991.[17)]

3. Lasing Characteristics and Scaling Law

The structure common to most VCSELs consists of two parallel reflectors which sandwich a thin active layer. The reflectivity necessary to reach the lasing threshold should be higher than 99.9%. Together with optical cavity formation, a scheme for injecting electrons and holes effectively into the small volume of the active region is necessary for a current injection device. AlAs oxidation is considered to be the most effective process for that purpose.

The VCSEL structure may provide a number of advantages, including ultralow threshold operation, because of its small cavity volume V. There are various scaling laws describing the VCSEL performances;[1–3,13)] they will be introduced in the following sections.

3.1 *Threshold current*

The threshold current I_{th} of surface-emitting lasers, which is common to semiconductor lasers, in general, can be expressed with threshold current density J_{th} by the following equation:

$$I_{th} = \pi(D/2)^2 J_{th} = \frac{eN_{th}}{\eta_i \tau_s} V \cong \frac{eB_{eff}}{\eta_i \eta_{spon}} N_{th}^2 V \propto V, \qquad (1)$$

where e is the electron charge, and V is the volume of the active region given by

$$V = \pi(D/2)^2 d. \qquad (2)$$

Thus, the threshold carrier density is given by

$$N_{th} = N_t + \frac{\alpha_a + \alpha_d + \alpha_m}{A_0 \xi}. \qquad (3)$$

Here, the parameters used are defined as follows.

α_a: Absorption loss coefficient averaged per unit length
α_d: Diffraction loss coefficient averaged per unit length
α_m: Mirror loss coefficient
A_0: Gain coefficient expressing differential gain $A_0 = dg/dN$ with g, optical gain per cm.
B_{eff}: Effective recombination coefficient
d: Total active layer thickness
D: Diameter of active region
L: Effective cavity length including spacing layers and penetration layers of Bragg reflectors
N_t: Transparent carrier density
τ_p: Photon lifetime in cavity
τ_s: Recombination lifetime
ξ: Optical energy confinement factor

$$\xi = \xi_t \xi_l$$

ξ_t: Transverse confinement factor
ξ_l: Longitudinal confinement factor or filling factor relative to stripe lasers

$$\xi_l = \begin{cases} d/L & \text{for thick active layer} \\ 2d/L & \text{for thin active layer at the loop of optical standing wave} \end{cases}$$

η_i: Injection efficiency, sometimes referred to as internal efficiency
η_{spon}: Spontaneous emission efficiency

Table I. Comparison of dimensions of stripe lasers and VCSELs.

Parameter	Symbol	Stripe laser	Surface-emitting laser
Active layer area	S	$3 \times 300\,\mu m^2$	$5 \times 5\,\mu m^2$
Active volume	V	$60\,\mu m^3$	$0.07\,\mu m^3$
Cavity length	L	$300\,\mu m$	$1\,\mu m$
Reflectivity	R_m	0.3	0.99–0.999
Optical confinement	ξ	3%	4%
Optical confinement (transverse)	ξ_t	3–5%	50–80%
Optical confinement (longitudinal)	ξ_l	50%	$2 \times 1\% \times 3$ (3QW)
Photon lifetime	τ_p	1 ps	1 ps
Relaxation frequency (low current levels)	f_r	<5 GHz	>10 GHz

As seen from eq. (1), we recognize that it is essential to reduce the volume of the active region in order to decrease the threshold current. Assuming that the threshold carrier density does not change significantly, if we reduce the active volume, we can reduce the threshold until we encounter an increase in diffraction loss and diffusion of carriers. We compare the dimensions of surface-emitting lasers and conventional stripe geometry lasers, as shown in Table I. It is notable that the volume of VCSELs may be $V = 0.06\,\mu m^3$, whereas that of stripe lasers remains $V = 60\,\mu m^3$. This directly reflects the threshold currents in that the typical threshold of stripe lasers has a range of tens of mA or higher, but that for VCSELs can be made less than sub-mA order by a simple carrier confinement scheme such as proton bombardment. It could even be as low as several tens of microamperes by implementing sophisticated carrier and optical confinement structures, as will be introduced later.

An early estimation of the threshold showed that the threshold current can be reduced proportionally to the square of the active region diameter. However, there should be a minimum value due to the decrease in the optical confinement factor that is defined by the overlap of the optical mode field and the gain region when the diameter becomes small. In addition, the extreme reduction of volume, in particular, in the lateral direction, is limited by the optical and carrier losses due to optical scattering, diffraction of lightwaves, nonradiative carrier recombination, and other technical imperfections.

3.2 *Output power and quantum efficiency*

We also discuss the differential quantum efficiency of the VCSEL. If we use a nonabsorbing mirror for the front reflector, the differential quantum efficiency η_d from the front mirror is expressed, using α as

$$\eta_d = \frac{\alpha_m}{\alpha_a + \alpha_d + \alpha_m} = \eta_i \frac{(1/L)\ln(1/R_f)}{\alpha + (1/L)\ln(1/\sqrt{R_f R_r})}, \qquad (4)$$

where α is the total internal loss ($= \alpha_a + \alpha_d$), and R_f and R_r are front and rear mirror reflectivities, respectively. The optical power output is expressed by

$$P_0 = \begin{cases} \eta_d \eta_{spon} C E_g I & I \le I_{th} \\ \eta_d \eta_{spon} C E_g I_{th} + \eta_d E_g (I - I_{th}) & I \ge I_{th}, \end{cases} \qquad (5)$$

where E_g is the band-gap energy, C is the spontaneous emission factor, and I is the driving current. On the other hand, the power conversion efficiency η_P far above the threshold is given by

$$\eta_P = \frac{P_0}{V_b I} = \eta_d \frac{E_g}{V_b}\left(1 - \frac{I_{th}}{I}\right) \cong \eta_d \frac{E_g}{V_b} \cong \eta_d, \tag{6}$$

where V_b is the bias voltage and the spontaneous component has been neglected. In the case of a surface-emitting laser, the threshold current can be very small, and therefore, the power conversion efficiency can be relatively high, i.e., higher than 50%. The power conversion efficiency is sometimes called the wall-plug efficiency.

3.3 Modulation bandwidth

The modulation bandwidth is given by

$$f_{3\,dB} = 1.55 f_r, \tag{7}$$

where f_r denotes the relaxation frequency which is expressed by

$$f_r = \frac{1}{2\pi\tau_s}\sqrt{\frac{\tau_s}{\tau_p}\left(\frac{I}{I_{th}} - 1\right)}. \tag{8}$$

The photon lifetime τ_p is given by

$$\tau_p = \frac{n_{eff}/c}{\alpha + \alpha_m}. \tag{9}$$

When the threshold current I_{th} is negligible relative to the driving current I, f_r can be expressed as

$$f_r \cong \frac{1}{2\pi\tau_s}\sqrt{\frac{\tau_s}{\tau_p}\frac{I}{I_{th}}} = \frac{1}{2\pi\tau_s}\sqrt{\frac{\tau_s}{\tau_p}\frac{\eta_i \eta_{spon} I}{eB_{eff}N_{th}^2 V}} \propto \sqrt{\frac{1}{V}}. \tag{10}$$

The relaxation frequency is inversely proportional to the square root of the active volume and it will be larger if we can reduce the volume as much as possible.

The photon lifetime is normally on the order of picoseconds, and is slightly shorter than that of stripe lasers. Since the threshold current can be very small in VCSELs, the relaxation frequency may be higher than that of stripe lasers even in low driving ranges. The threshold carrier density N_{th} can be expressed in terms of the photon lifetime that represents the cavity loss, and is given, by using eqs. (9) and (3), as

$$N_{th} = N_t + \frac{1}{(c/n_{eff})}\frac{1}{(dg/dN)}\frac{1}{\xi}\frac{1}{\tau_p}. \tag{11}$$

It is noted that the threshold carrier density may be low if the differential gain dg/dN, confinement factor ξ, and photon lifetime τ_p are large.

On the other hand, the free spectral range of the Fabry–Perot cavity is expressed, in terms of cavity length L_c, by

$$\Delta\lambda = \frac{\lambda_0^2}{2n_{eff}}\frac{1}{L_c} \propto \frac{1}{L_c} \tag{12}$$

Dynamic single-mode operation is maintained because of the large mode separation resulting from the short cavity length of VCSELs. The wide frequency tuning range has the same basis.

Because of the above physics, the VCSEL may provide a number of advantages.

a) Ultralow-threshold operation due to its small cavity volume.
b) Dynamic single-mode operation.
c) Wide and continuous wavelength tuning.
d) High relaxation frequency even at low driving current.
e) Easy coupling to optical fibers.
f) Monolithic fabrication and easy device separation without the need for perfect cleaving.
g) Vertical stack integration by micro electro mechanical systems (MEMS) technology.

4. Technical Progress

In the following sections, we present the technical progress of surface-emitting lasers for short- and long-wave length bands.

4.1 Surface-emitting laser in long-wavelength band

4.1.1 GaInAsP/InP VCSEL

The author realized the first surface-emitting laser device fabricated using the GaInAsP/InP system in 1978 and reported it in 1979.[7] However, the GaInAsP/InP system that is conventionally used in trunk communication systems, along with a temperature controller, presents some major difficulties in fabricating high-efficiency VCSELs because of the following reasons.

(a) Auger recombination and inter-valence band absorption (IVBA) are substantial.
(b) The index difference between GaInAsP and InP is too small to make distributed Bragg reflector (DBR) mirrors.
(c) Conduction band offset is small.

Hybrid mirror technologies are being developed. One is to use a semiconductor/dielectric reflector.[18] Thermal problems in CW operation have been extensively studied. A MgO/Si mirror with good thermal conductivity was demonstrated to enable room-temperature CW operation for 1,300 nm surface-emitting lasers for the first time.[19] However, better results were subsequently obtained using Al_2O_3/Si mirrors.[20]

Another conceivable technology is epitaxial bonding of the GaInAsP/InP active region and GaAs/AlAs mirrors. The CW threshold of 0.8 mA[21] and the maximum operating temperature of up to 71 °C was reported for 1,550 nm VCSELs with double bonded mirrors.[22] In 1998, a tandem structure of a 1,300 nm VCSEL optically pumped by a 850 nm VCSEL was demonstrated to achieve an output power of 1.5 mW.[23] However, the cost of wafer consumption in wafer fusion devices may become the final bottleneck to low-cost commercialization. The importance of 1,300 or 1,550 nm devices is currently increasing, because parallel lightwave systems are necessary to satisfy the rapid increase in information transmission capacity in LANs.

4.1.2 AlGaInAs/AlGaInAs and other-material VCSEL

It is known that the AlGaInAs/InP system can provide a good temperature characteristic because of its large conduction band offset together with the AlAs/AlInAs superlattice multi-quantum barrier (MQB) for the oxide aperture, and a good temperature characteristic has been demonstrated in edge emitters.[24]

The crystal growth of AlAs/GaAs DBR on an InP-based active layer has also been demonstrated.[25] Using this system, the first monolithic VCSEL demonstrating room-temperature CW operation in the long-wavelength region

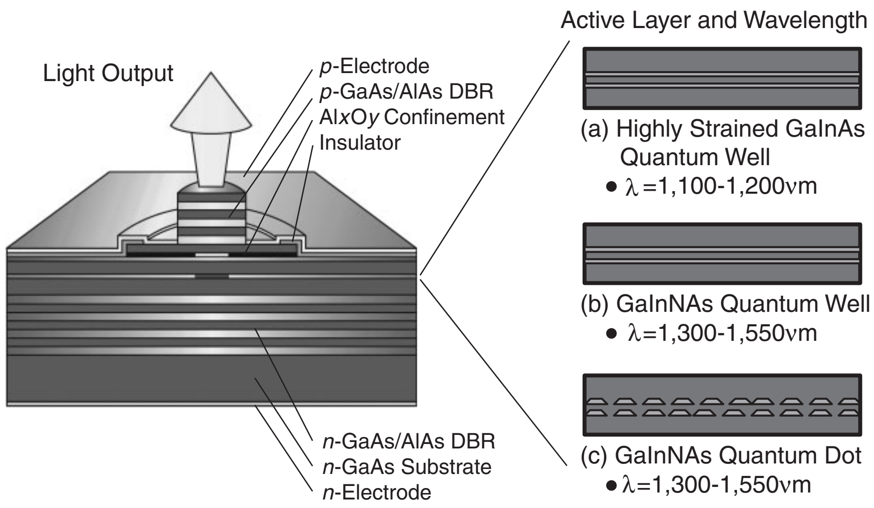

Fig. 4. Choices of long-wavelength VCSELs formable on GaAs substrate (after T. Miyamoto, unpublished).

was fabricated. In addition, GaAsSb QWs formed on a GaAs substrate have been demonstrated for application to 1,300 nm VCSELs.[26] An AlGaAsSb/GaAs system has been found to form a good DBR.[27] A tunnel junction and AlAs oxide confinement structures may be very effective in long-wavelength VCSEL development.[28] The author tried to introduce a reverse-biased tunnel junction to make a tandemly connected active layers in 1984.[29] This supposed to be the first attempt of tunnel injection in VCSELs.

4.1.3 Long-wavelength VCSELs on GaAs substrate

Some possible choices of long-wavelength VCSELs formable on GaAs are shown in Fig. 4. They will have a great impact upon the realization of high-performance devices. One interesting system is GaInNAs lattice-matched to GaAs. This system was first made by Kondow *et al.*[30] by gas source molecular beam epitaxy (GSMBE) and $\lambda =$ 1,190 nm stripe lasers with the nitrogen content of 0.4% were fabricated. Room-temperature CW operation of horizontal cavity lasers exhibiting a threshold current density of 1.5 kA/cm^2 has been achieved. Also, stripe geometry lasers with a threshold of 24 mA at room temperature were demonstrated.[31] It is reported that the characteristic temperature is to 120 K at around near room temperature.[32] If we can increase the nitrogen content up to 5%, the wavelength band of 1,550 nm may be covered. The author reported the concept of long-wavelength GaInNAs VCSELs in 1996.[33] In particular, GaAs/AlAs Bragg reflectors can be incorporated on the same substrate, and AlAs oxidation can be utilized.[24] Some considerations of device design have since been presented.[34] Larson *et al.* realized the first VCSEL using this system.[35] We first achieved lasing operation with GaInNAs edge emitters, grown by chemical beam epitaxy (CBE), that exhibited $T_0 > 270$ K.[36] We demonstrated a GaInNAs VCSEL grown by MOCVD.[37,38]

While conducting research on GaInNAs lasers, we found that a highly strained GaInAs/GaAs system containing high In content (=40%) can provide an excellent temperature characteristic,[39] i.e., operation at $T_0 > 200$ K. This system should be viable for $\lambda \cong 1{,}200$ nm VCSELs for silica-fiber-based high speed LANs.[40] We show typical *I–L* and temperature characteristics of a highly strained GaInAs/GaAs VCSEL in Fig. 5. This particular device was formed on a (311)B substrate. It is noted that we can achieve temperature-insensitive operation of semiconductor lasers by properly designing the gain center and cavity resonance. Such an operation has been confirmed.

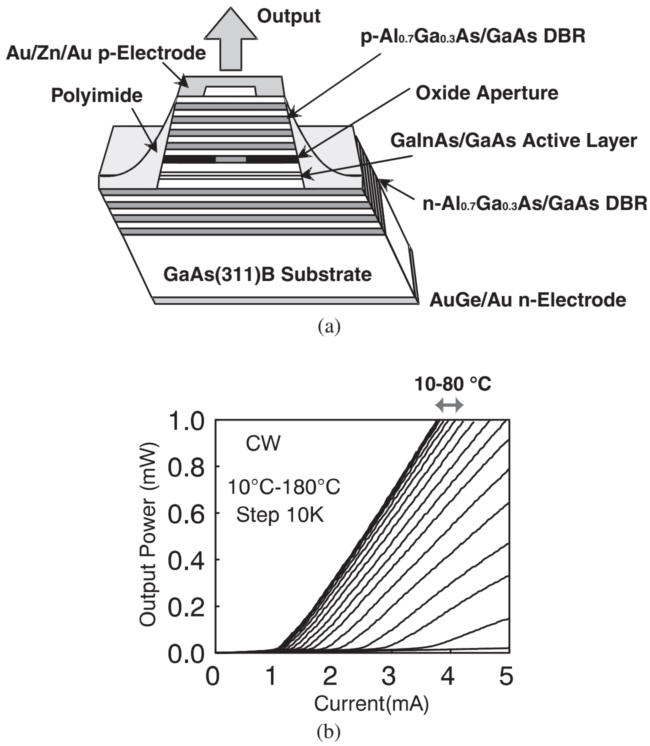

Fig. 5. Highly strained 1,200-wavelength nm GaInAs/GaAs VCSEL grown on (311)B substrate.[29] (a) Device structure and (b) its *I–L* characteristics.

It is highly beneficial to use a quantum dot structure for the long-wavelength active layer on a GaAs substrate. A 1150 nm GaInAs-dot VCSEL was reported with a threshold current of 0.5 mA.[41] Thus, these kinds of GaAs-based systems will substantially improve the surface-emitting laser performance in the long-wavelength range. The merits of this system are as follows: (a) ultra-low-threshold devices are considered, (b) carrier diffusion from dots to the surrounding region is minimized to confine carriers, and (c) higher gain can be expected if uniform dots can be formed.

4.2 Surface emitting laser in mid-wavelength band

4.2.1 980 nm GaInAs/GaAs VCSEL

For the 980 nm wavelength band, the GaInAs/GaAs strained pseudomorphic system grown on a GaAs substrate has been used in semiconductor lasers for pumping optical fiber amplifiers. This system exhibits a high laser gain and has been introduced into surface-emitting lasers together with GaAs/AlAs multilayer reflectors. A low threshold (1 mA at CW) was first demonstrated by Jewell *et al.*[33] The threshold current of VCSELs has been reduced to sub-milliampere order at various institutions around the world.[42,43] Moreover, a threshold of less than 100 µA for room-temperature CW operation by introducing oxide current and optical confinement has been reported.[44,45] The theoretical expectation is less than 10 µA, if sufficient current and optical confinement structure can be introduced.[46,47]

In 1995, we demonstrated a novel laser structure employing a selective oxidizing process applied to AlAs, which is a material used in multilayer Bragg reflectors.[48] The active region is three quantum wells consisting of 8 nm GaInAs strained layers. The Bragg reflector consists of GaAs/AlAs quarter-wavelength stacks of 24.5 pairs. After etching the epitaxial layers, including the active layer and two Bragg reflectors, the sample was treated in a high-temperature oven with water vapor bubbled by nitrogen gas. The AlAs layers are oxidized preferentially by this process and native aluminum oxide is formed at the periphery of the etched mesas. It is recognized from the scanning electron microscopy (SEM) image that only the AlAs layers in DBR have been oxidized. The typical size is 20 µm for a core starting from a 30-µm-diameter mesa. We have achieved a power output of approximately 1 mW and a sub-microampere threshold. The nominal lasing wavelength is 980 nm. We have made a smaller diameter device of 5 µm starting from a 20 µm mesa. The minimum threshold achieved is 70 µA for room-temperature CW operation.

Regarding the output power of VCSELs, a relatively high power of more than 50 mW may be possible.[49] Actually, the power conversion efficiency of 50% has been reported.[50] Also, high-efficiency operation at relatively low driving levels, i.e., 3–4 mA, which had been difficult to achieve in stripe lasers, was achieved. This is due to the availability of low-resistivity DBR with an Al-oxide aperture. In fact, in devices of approximately 1 µm in diameter, power conversion efficiencies of higher than 20% have been reported.[51,52]

A high power of close to 200 mW has been demonstrated for a large device Ulm University.[53] In a two-dimensional array involving 1000 VCSELs with active cooling, more than 2 W of CW output was achieved.[54]

High-speed modulation is also possible at low driving currents of around 1 mA in the low-power-consumption devices, this is important in low-power interconnect applications enabling >10 Gbits/s transmission or 1 Gbit/s zero-bias operation.[55] Experiments of transmission over 10 Gbits/s and zero-bias transmission have been reported. We measured an eye diagram in an experiment of 10 Gbits/s transmission through a 100 m multimode fiber.[56]

4.2.2 980 nm GaInAs/GaAs VCSEL on GaAs substrate

Concerning the polarization of VCSEL light output, most devices grown on GaAs(100) substrates show unstable polarization states because of isotropic material gain and symmetric cavity structures. VCSELs grown by MBE on GaAs(311)A substrates, however, show a very stable polarization state.[57] Trials of growth on (GaAs)B substrates by MOCVD have also been performed.[58,59] In this section, we introduce a single transverse mode and polarization-controlled VCSEL grown on a GaAs(311)B substrate. Both higher-order transverse modes and a non-lasing orthogonal polarization mode are well suppressed with a suppression ratio of over 25 dB.[60]

The design of a top-emitting VCSEL (311)B fabricated by low-pressure MOCVD[61] is as follows. The bottom n-type DBR consists of 36 pairs of $Al_{0.7}Ga_{0.3}As$/GaAs doped with Se. The top p-type DBR consists of 21 pairs of Zn-doped $Al_{0.7}Ga_{0.3}As$/GaAs and a 70-Å-thick AlAs high-C-doped layer inserted at the upper AlGaAs interface by the carbon autodoping technique proposed by us.[53] The active layer consists of three 8-nm-thick $In_{0.2}Ga_{0.8}As$ quantum wells and 10 nm GaAs barriers surrounded by $Al_{0.2}Ga_{0.8}As$ to form a cavity. An 80-nm-thick AlAs layer is introduced on the upper cavity spacer layer to create oxide confinement. We oxidized the AlAs layer of the etched $50 \times 50\,\mu m^2$ mesa at 480 °C for 5 min in N_2/H_2O atmosphere by bubbling in 80 °C water and formed an oxide aperture of $2.5 \times 3.0\,\mu m^2$. The threshold current was 260 µA, which is comparable to the lowest value reported for non-(100) substrate VCSELs. The threshold voltage is 1.5 V and the maximum output power is 0.7 mW at 4 mA.

Throughout the entire tested driving range ($I < 16I_{th}$), a high side-mode suppression ratio (SMSR) of over 35 dB and an orthogonal polarization suppression ratio (OPSR) of over 25 dB were achieved simultaneously. The single polarization operation was maintained under a 5 GHz modulation condition.[62]

4.3 Surface-emitting lasers in visible and near-infrared–red band

4.3.1 850 nm GaAlAs/GaAs VCSEL

A GaAlAs/GaAs laser can employ almost the same circular buried heterostructure (CBH) as the GaInAsP/InP laser. In order to decrease the threshold, the active region is also constricted by the selective meltback method. In 1986, a threshold of 6 mA was demonstrated for an active region of 6 µm diameter and ~6 mA under pulsed operation at 20.5 °C.[10] The first room-temperature CW operation was achieved in 1988, as already mentioned.[11,12]

In Fig. 6, we show a 850 nm GaAs-based VCSEL fabricated employing AlAs selective oxidation.[63] In production levels, sub-mA thresholds and 10 mW output have been achieved. A power conversion efficiency of 57% has also been demonstrated.[64] Some optical links have already become commercially available. The price of low-skew multimode fiber ribbons may be a key issue for realizing inexpensive multimode fiber-based data links.

For the reliability of VCSELs, 10^7 h of room-temperature operation was estimated on the basis of the results of an acceleration test at high temperature using proton-defined devices.[65] Some preliminary test results have been reported

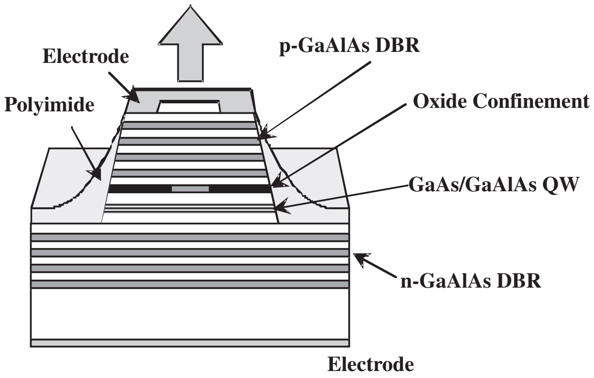

Fig. 6. Typical structure of a 850-nm-band GaAs-based VCSEL.[56)]

for oxide-defined devices exhibiting no substantial negative failures.

4.3.2 780 nm GaAlAs/GaAs VCSEL

The VCSEL at the wavelength of 780 nm was demonstrated in 1987 by optical pumping, and a current-injection device was developed in this wavelength range for the first time by Lee *et al.*[66)] If we select the Al content x to be 0.14 for $Ga_{1-x}Al_xAs$, the wavelength can be as short as 780 nm. This is a common wavelength for compact disc lasers. When a quantum well is used for the active layer, blue shift should be taken into account. We describe such a design below.[67)] The $Ga_{0.86}Al_{0.14}As$ active layer is formed by a superlattice consisting of GaAs (33.9 Å) and AlAs (5.7 Å) with 14 periods. The DBR is made of AlAs-$Al_{0.35}Ga_{0.65}As$-$Al_{0.3}$-$Ga_{0.7}As$-$Al_{0.35}Ga_{0.65}As$ with one period. The n-DBR has 28.5 pairs and p-DBR consists of 22 pairs. The threshold in 1991 was 4–5 mA and the output was 0.7–0.8 mW. Later on, MQW made with Al ($x = 0.1/0.3$) was introduced, and a threshold of 200 µA and an output of 1.1 mW were demonstrated.

4.3.3 AlGaInP red VCSEL

Generally, light-emitting devices in short-wavelength regions may have more severe problems regarding operation than those in long-wavelength regions, since the photon energy is high and p-type doping is technically more difficult to perform. If aluminum (Al) is included in the system, the degradation due to Al oxidation would be appreciable. The AlGaInP/GaAs system that emits red light in the range of 630–670 nm is considered as the laser for the first-generation digital video disc system. Red-light GaInAlP/GaAs VCSELs have been developed and room-temperature operation exhibiting a sub-milliampere threshold has been demonstrated. Sub-milliampere thresholds, 11% power conversion efficiency and 8 mW output power have been achieved,[68)] and 60 °C operation has been reported.[69)] More recently, the red VCSEL has been commercialized for application to printers and plastic fiber communications.

4.4 Surface-emitting lasers in green–blue–UV band

Visible surface-emitting lasers are extremely important for disks, printers, and display applications. In particular, red, green and blue surface emitters may provide much wider technical applications, if realized. GaN and related materials can cover wide spectral ranges from blue to UV region for LEDs and LDs.[70,71)] The reported reliability of GaN-based lasers also indicates good potential as a material for surface-emitting lasers.[72)] Optical gain is one of the important parameters in estimating the threshold current density of GaN-based VCSELs. The estimation of linear gain for GaN/$Al_{0.1}Ga_{0.9}N$ quantum wells is carried out using the density-matrix theory with intraband broadening. The transparent carrier density of GaN is higher than that of other III–V materials such as GaAs, presumably because of its heavy electron and hole masses. Generally, the effective masses of electrons and holes depend on the band-gap energy. Thus it seems that the wide-band-gap semiconductors require higher transparent carrier densities than do narrow-band-gap materials. The introduction of quantum wells for wide-band-gap lasers is very effective. This result indicates that the GaN/$Al_{0.1}Ga_{0.9}N$ QW is useful for low-threshold operation of VCSELs.

Trials for realizing green to UV VCSELs have just begun. Some optical pumping experiments have been reported. It is necessary to establish some process technologies for device fabrication, such as etching, surface passivation, substrate preparation, metallization and current confinement formation. We have conducted a preliminary study on dry etching of a GaN system by chlorine-based reactive ion beam etching, and it was found to be feasible.

The GaN system has high potential for use in short-wavelength lasers. AlN/GaN DBR and ZrO/SiO_2 DBR have been formed for VCSELs,[73,74)] and a photopumped GaInN VCSEL has been reported.[75–77)]

5. Advanced Technology

A VCSEL appropriately designed for telecom applications can now provide single-wavelength, single-transverse-mode, stable-polarization operation. A wide variety of functions, such as frequency tuning, amplification, and filtering, should be integrated.

Moreover, a two-dimensional (2-D) parallel optical logic system can deal with a large amount of image information with high speed. Micromachining technology and MEMS will also be very helpful.[78)] By using VCSEL and micromachining technology, we demonstrated a temperature-insensitive-surface normal Fabry–Perot filter for add-drop filtering in WDM. Also, Christensen[79)] and Koyama *et al.*[80)] achieved temperature-insensitive operation by adoptong this method, as shown in Fig. 7. Light beam manipulation technology using the MEMS scheme will open up a new field of optical switching and routing in large-scale optical exchange systems.

A densely packed array has also been demonstrated for making high-power lasers and coherent arrays. For realizing coherent arrays, coherent coupling of these arrayed lasers has been attempted using a Talbot cavity, and phase compensation has also been considered. A wide variety of functions, such as frequency tuning, amplification, and filtering, can be integrated with surface-emitting lasers by stacking. Parallel photonic devices and optical subsystems are now being developed, and the application areas of these devices are broadening toward the realization of high-speed LANs, optical interconnects, and optical links,

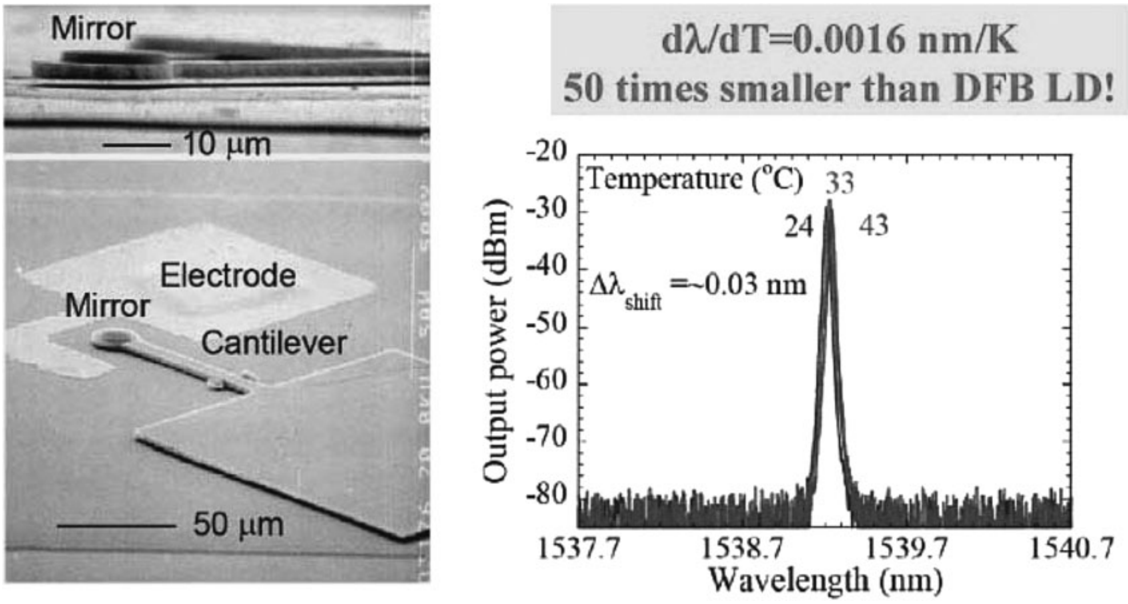

Fig. 7. Temperature-insensitive VCSEL.

Table II. Applications of VCSELs.

Technical fields	Systems
1. Optical communications	Local area networks, optical links, mobile links
2. Computer optics	Computer links, optical interconnects, high-speed/parallel data transfer, storage area networks
3. Optical memory	CD, DVD, near field, multibeam, initializer
4. Optoelectronic equipment	Printer, laser pointer, mobile tools, home appliances
5. Optical information processing	Optical processors, parallel processing
6. Optical sensing	Optical fiber sensing, bar-code readers, encoders, computer mouse
7. Displays	Array light sources, high-efficiency light-sources, projection TV
8. Illumination	Multibeam searchlights, micro-illuminators, adjustable illumination
9. Automotive systems	Automotive data transfer and control, automobile radar

optical sensing, for example. The ultraparallel and ultra-high-speed photonics will also open up a new era in industry.

In Table II, we show possible applications of VCSELs. The VCSEL itself is basically an exploratory device and is suitable for Gigabit Ethernet and fiber channel applications. It is making headway into a higher class of data communication systems such as 10 Gbit Ethernet, high-speed LANs, optical interconnects and optical links. Moreover, long-wavelength VCSELs have been developed for long-distance metropolitan-area networks (MANs). It is noted that continuous and wide-range wavelength tunability is a viable solution among many other candidates for this purpose.[81,82] The replacement of DFB lasers may be a disruptive technology.[79]

It is found that the temperature dependences of threshold and quantum efficiency could be eliminated by properly designing the device structure and material. The highly strained GaInAs/GaAs emitting a 1200 nm band is one such example,[82] and the GaInNAs system may be another.

The application to optical disks appears to be another disruptive technology of simply replacing the currently existing lasers and pickups by near-field optics.[83] There is also the advantage of being able to form a 2-D module together with planar microlens arrays.[84] A GaN VCSEL, if realized, may open up new fields.

6. Summary

Technology for surface-emitting lasers has been developed and high-performance devices are being realized.[85,86] A threshold current below 10–100 μA was demonstrated and extremely low thresholds of less than 1 μA are the focus of research. Reasonably high power of greater than 200 mW and power conversion efficiency better than 57% have also been demonstrated. These values are equivalent to or better than those of conventional stripe lasers.

Long-wavelength devices are facing some difficulties regarding high temperature and large output, but there are several innovative technologies to solve these problems. Very short-wavelength lasers, if realized, may give rise to a wider range of applications. The surface-emitting laser is now considered the key component in ultralow-power-consumption and high-power applications.

Vertical optical interconnects of LSI chips and circuit boards and multiple fiber systems may be the most interesting fields related to VCSELs. From this point of view, the device should be as small as possible. Future process technology, including epitaxy and etching, will significantly change the situation of VCSELs. Some optical technologies have already been introduced to various subsystems, and in addition, the arrayed microoptic technology will be very useful for advanced systems.

The most promising application will be multi-gigabit LANs. GaAs VCSELs emitting 850 nm standardized wavelength are being mass-produced for >1 Gbits/s LAN and simple optical links. For high-end systems, 1,300–1,550 nm-wavelength devices are required. In order to establish an appropriate module technology utilizing VCSELs, a micro-optical bench (MOB) is currently being investigated, together with a planar microlens array.

Acknowledgements

The author would like to thank Professor Emeritus Y. Suematsu for his continuous encouragement. He also thanks Professors F. Koyama, K. Kobayashi, T. Miyamoto, H. Uenohara, and N. Nishiyama, Dr. T. Kageyama, Dr. Y. Aoki, and other laboratory members for their collaboration and assistance in preparing this manuscript. A Grant-in-Aid for COE Program #07CE2003 from the Ministry of Education, Culture, Sports, Science and Technology supported this work.

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