INVITED PAPER

Vertical-Cavity Surface-Emitting Laser (VCSEL)

The alloy semiconductor laser has emerged and matured to a level that impacts the daily life of many people on the planet. One such form is the vertical-cavity surface-emitting laser (VCSEL). The development, physics, and progress of these important devices are reviewed in this paper.

By Kenichi Iga

ABSTRACT | 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, including storage area networks (SANs) and wide optoelectronics fields. In this paper, we will review its physics and the progress of technology covering the spectral band from infrared to ultraviolet by featuring materials and fabrication technology. Performances such as threshold, output power, polarization, modulation, and reliability are introduced. Last, we will touch on its future prospects.

KEYWORDS | Distributed Bragg reflector (DBR); gigabit Ethernet; local area network (LAN); microlens; multilayer; quantum well; semiconductor laser; surface-emitting laser (SEL); vertical-cavity surface-emitting laser (VCSEL)

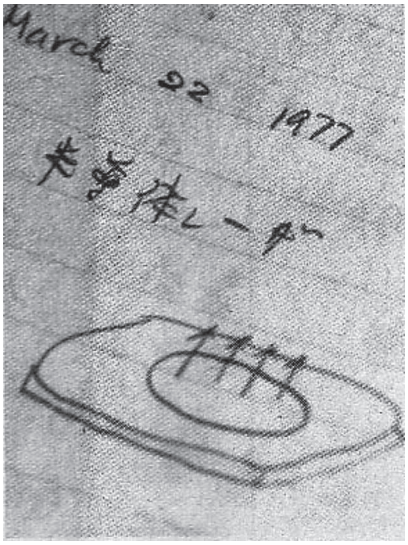

Fig. 1. *Sketch of the VCSEL [1].*

I. INTRODUCTION

The vertical-cavity surface-emitting laser (VCSEL), as shown in Fig. 1, is a new class of semiconductor lasers that can be monolithically fabricated. The author of this paper came up with an idea of the VCSEL device in 1977 [1], [2]. The first device came out in 1979, where we used a 1300-nm wavelength GaInAsP/InP material for active region [3]–[5]. VCSELs based on GaAs have been extensively studied [6]–[8]. The first room-temperature continuous-wave (CW) device using GaAs material was demonstrated in 1988 [9], [10]. Since 1992, some of 980-, 850-, and 780-nm devices were commercialized into lightwave systems. Aiming at exploring applications, 1300–1550-nm-long wavelength [11]–[14], red color AlGaInAs, and blue-ultraviolet GaN devices are now being developed [15], [16].

II. DEVICE PHYSICS AND THE 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 normally be higher than 99.9%. Together with the optical cavity formation, the scheme for injecting electrons and holes effectively into a small volume of an active region is necessary for the current injection device.

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Table 1 VCSEL Technology Map and Wavelength

Wavelength	Materials	Exploratory	Emerging	Disruptive
410 nm	GaInAlN/GaN	Disks	x	Display
550 nm	GaInAlN/GaN	x	x	x
650 nm	AlGaInP/ GaAs	x	POF*1	Printer
780 nm	GaAlAs/GaAs	Printer	Printer	x
850 nm	GaAlAs/GaAs	10Gbit-Ethernet	Gbit-Ethernet	LAN*2/Link
980 nm	GaInAs/GaAs	Interconnect	x	x
1200 nm	GaInAs/GaAs	x	x	LAN
1300 nm#)	GaInAsP/InP	LAN	x	x
1550 nm#)	GaInAsP/InP	LAN	x	MAN*3

#) GaInAsP/InP, AlGaInAs/AlGaInAsAlGaInAs/InP, AlAs/AlInAs superlattice, GaAsSb, AlGaAsSb/GaAs, GaInNAs

x: undefined   *1:Plastic Optical Fiber *2:Local Area Network *3:Metropolitan Area Network

The VCSEL structure may provide a number of advantages, including ultralow threshold operation due to its small cavity volume V. We may have some scaling laws describing the VCSEL performances [6]–[8].

A. Threshold Current

The threshold current I_{th} of surface-emitting lasers (SELs) and common to semiconductor lasers, in general, can be expressed by [8]

$$I_{th} \propto V \tag{1}$$

where V is the volume of the active region.

As seen from (1), we recognize that it is essential to reduce the volume of the active region in order to decrease the threshold current. Assume that the threshold carrier density does not change much if we reduce the active volume, and we can reduce the threshold until we meet an increase of diffraction loss and diffusion of carriers. When we compare the dimensions of SELs and conventional stripe geometry lasers, it is noticeable that the volume of VCSELs could be $V = 0.06\ \mu\text{m}^3$, whereas that for stripe lasers remains $V = 60\ \mu\text{m}^3$. This directly reflects the threshold currents, where a typical threshold of stripe lasers is in the range of tens of mA or higher, but that for VCSELs can be less than a submilliampere (sub-mA) by a simple carrier confinement scheme such as AlAs oxidation. It could be even as low as several tens of microamperes by implementing sophisticated carrier and optical confinement structures.

An early stage estimation of a 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 originating from the decrease of the optical confinement factor that is defined by the overlap of the optical mode field and gain region when the diameter becomes small. In addition to this, 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 lightwave, and nonradiative carrier recombination, and other technical imperfections.

B. Modulation Bandwidth

The 3-dB modulation bandwidth is given by [8]

$$f_{3\ \text{dB}} \propto \sqrt{\frac{1}{V}}. \tag{2}$$

The modulation frequency is inversely proportional to the square root of an active volume, and it can be larger if we can reduce the volume as much as possible. A dynamic single-mode operation is maintained due to the large mode separation coming from short cavity lengths of VCSELs. A

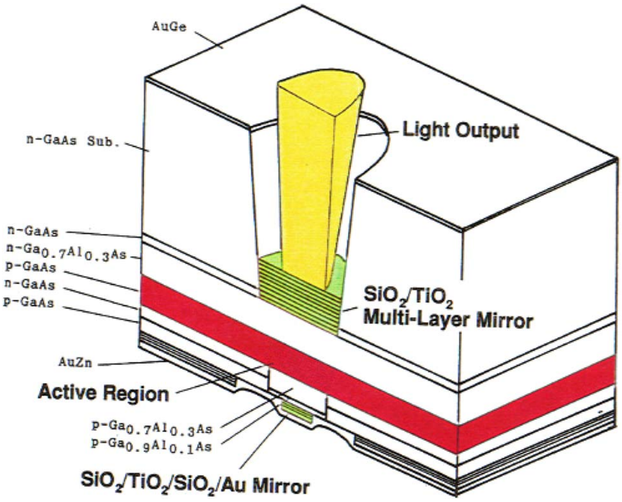

Fig. 2. *VCSEL achieving room-temperature CW operation in 1988 [9], [10].*

Table 2 Applications of VCSELs

Technical Fields	Systems
1. Optical Communications	LANs, Optical links, Mobile links, etc.
2. Computer Optics	Computer links, Optical interconnects, High speed/Parallel data transfer, etc.
3. Optical Memory	CD, DVD, Near field, Multi-beam, Initializer, etc.
4. Optoelectronic Equipments	Printer, Laser pointer, Mobile tools, Home appliances, etc.
5. Optical Information Processing	Optical processors, Parallel processing, etc.
6. Optical Sensing	Optical fiber sensing, Bar code readers, Encoders, etc.
7. Displays	Array light sources, High efficiency light-sources,
8. Illuminations	Multi-beam search-lights, Micro illuminators, Adjustable illuminations, etc.

wide-frequency tuning range is based on the same reason. Due to these physics, the VCSEL may provide a number of advantages as follows [15], [16]:

1) ultralow threshold operation is expected from its small cavity volume;
2) dynamic single-mode operation;
3) wide and continuous wavelength tuning;
4) large relaxation frequency, even at small driving current;
5) easy coupling to optical fibers;
6) monolithic fabrication and easy device separation without perfect cleaving requirement;
7) vertical stack integration by microelectromechanical system (MEMS) technology.

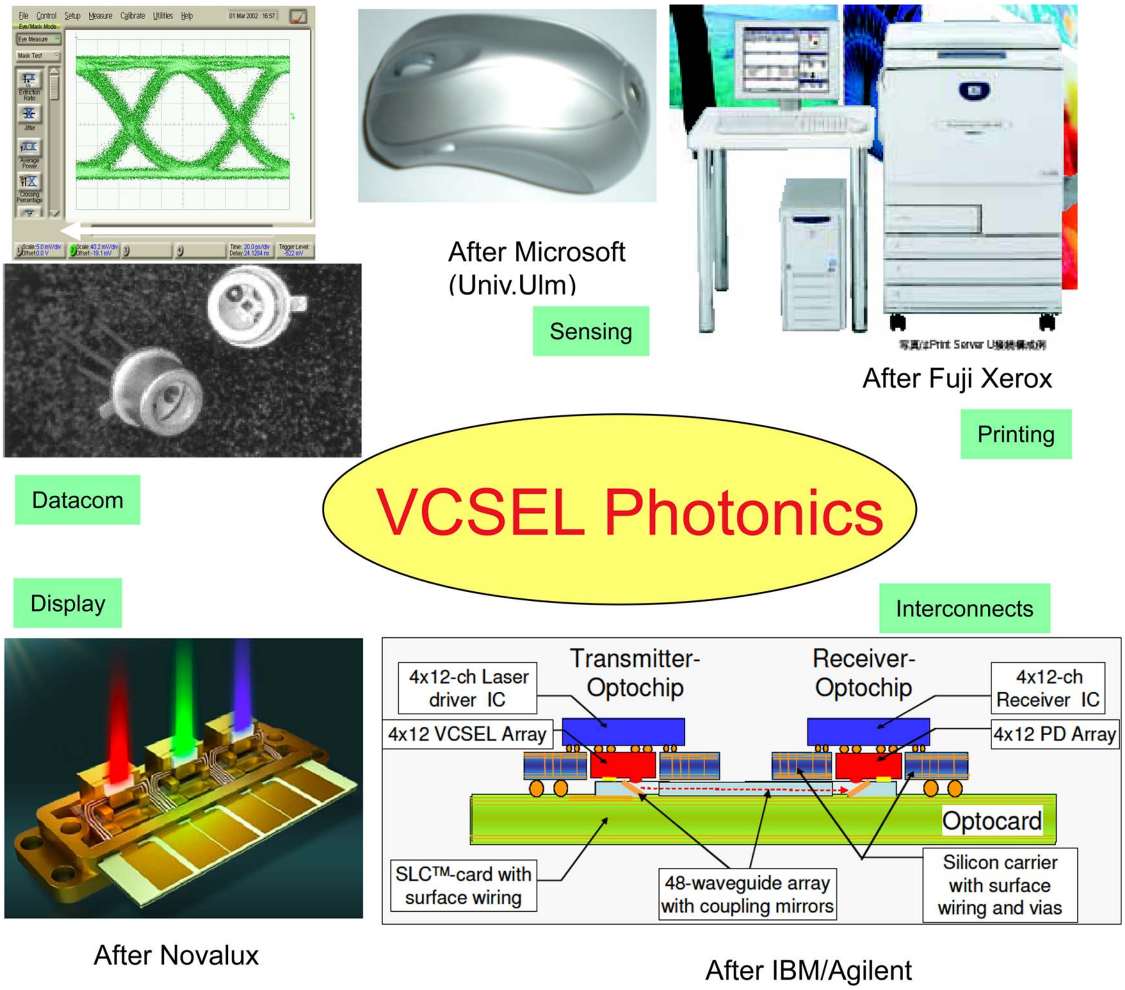

Fig. 3. ***Application of VCSEL photonics.***

III. TECHNICAL PROGRESS

We show the status of VCSELs for a wide range of spectral bands in Table 1. Possible choices and technology of semiconductors have been extensively studied for quantum-well and mirror formation, and the current confinement scheme. An AlAs oxidation is considered to be the most effective process to perform it.

VCSELs based on GaAs have been extensively studied [11]–[14]. The first room-temperature CW device as shown in Fig. 2 using GaAs material was demonstrated in 1988 [9], [10]. Since 1992, some of 980-, 850-, and 780-nm devices were commercialized into lightwave systems [15], [16].

In the author's group, some key concepts have been proposed: the quantum-well VCSEL, the tandem VCSEL, the multiquantum barrier (MQB), the 1200-nm GaInAs/GaAs VCSEL, modulation schemes, the phased array VCSEL, the Talbot cavity VCSEL, tunneling injection, and so on [15], [16].

IV. PROSPECTS

In Table 2, we show possible application areas of VCSELs. The VCSEL itself is basically an exploratory device and generated gigabit Ethernet and fiber channel applications [15], [16]. It is emerging into higher class of data communication system such as 10-Gb Ethernet, high-speed LANs, optical interconnects, optical links, and so on. Moreover, long-wavelength VCSELs have been developed toward 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. The VCSEL has been contributing to the "green information, communication, and energy (ICE)" technology in various aspects by featuring low-power and high-speed performances. It has already been introduced to various lightwave subsystems, including gigabit Ethernet and storage area networks (SANs). Optical interconnect of large-scale integration (LSI) chips and circuit boards and multiple fiber systems as in supercomputers and personal computers (PCs) is the most interesting field related to VCSELs. Also, VCSEL-based photonics created other various fields such as laser printers, computer mice, optical sensors, and so on as depicted in Fig. 3. The arrayed microoptics technology [17] will be very useful in advanced systems.

The concept of VCSELs has been expanded into nanophotonic and photonic crystal fields. The ultraparallel and ultrahigh-speed photonics based upon sophisticated VCSELs including MEMS and integrated optics will begin a new era in the 21st century. ■

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