VCSEL -Its History and Prospects for Green Microoptics-

Kenichi Iga
Tokyo Institute of Technology, Emeritus Professor
kiga@vcsel.org

Abstract - *In this talk, we will revie wthe history and the progress of VCSEL 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. Lastly, we will touch on its future prospects fro green microoptics for ICT.* **Keywords:** VCSEL, microoptics, green ICT, array, computer mouse, laser printer

I. INTRODUCTION

The vertical cavity surface emitting laser (VCSEL) as shown in Fig. 1 is a popularly known semiconductor laser that can be monolithically fabricated. The present author suggested the device of VCSEL in 1977 [1]. The first device came out in 1979 [2], where we used a 1300nm wavelength GaInAsP/InP material for active region [3]-[5]. VCSELs based on GaAs have been extensively studied[3]-[5]. The first room temperature continuous wave (CW) device using GaAs material was demonstrated in 1988 .

II. DEVICE PHYSICS AND SCALING LAW

The structure common to most of 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 small volume of active region is necessary for current injection device. The VCSEL structure may provide a number of advantages explained laser [3][4].

A. Threshold Current

The threshold current I_{th} of surface emitting lasers and common to semiconductor lasers, in general, can be expressed by the expression [3];

$$I_{th} \propto V_a \qquad (1)$$

where V_a is the volume of active region.

As seen from this expression, we recognize that it is essential to reduce the volume of active region in order to decrease the threshold current. Assume that the threshold carrier density does not change so much if we reduce the active volume, we can reduce the threshold until we meet an increase of diffraction loss and diffusion of carriers. When we compare the dimensions of surface emitting lasers and conventional stripe geometry lasers, it is noticeable that the volume of VCSEL's could be V=0.06 μm^3, whereas that for stripe lasers remains V=60 μm^3. This directly reflects the threshold currents that the typical threshold of stripe lasers is ranging tens of mA or higher, but that for VCSEL's is able to be less than sub-mA by a simple carrier confinement scheme such as AlAs oxidation. It could be even as low as several ten micro-Amperes by implementing sophisticated carrier and optical confinement structures.

B. Modulation Bandwidth

The 3dB modulation bandwidth is given by [3];

$$f_{3dB} \propto \sqrt{1/V_a}$$

The modulation frequency is inversely proportional to the square root of active volume and it can be larger, if we can reduce the volume as small as possible. Dynamic single mode operation is maintained due to the large mode separation coming from short cavity length of VCSEL's. Wide frequency tuning range is based on the same reason. Due to these physics the VCSEL may provide a number of **advantages** shown below [3];

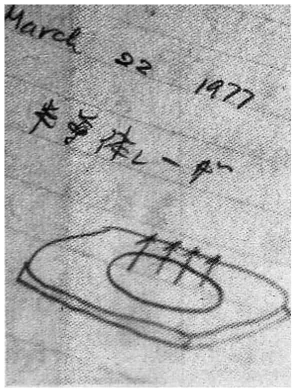

Fig. 1 A sketch of vertical cavity surface emitting laser (VCSEL) [1].

a) Ultra-low threshold operation is expected from its small cavity volume.
b) Dynamic single mode operation.
c) Wide and continuous wavelength tuning.
d) Large relaxation frequency even at small driving current.
e) Easy coupling to optical fibers.
f) Monolithic fabrication and easy device separation without perfect cleaving requirement.
g) Vertical stack integration by MEMS technology.
h) 2D arrayed configuration.

III. TECHNICAL PROGRESS

Possible choices and technology of semiconductors have been extensively studied for quantum wells and mirror formation, and 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 [1]-[4]. The first room temperature continuous wave (CW) device using GaAs material was demonstrated in 1988. Since 1992, some of 980, 850 and 780nm devices were commercialized into lightwave systems [5],[6].

In the author's group, some key concepts have been proposed; Quantum-well VCSEL, MQB (Multi-Quantum Barrier), 1,200nm GaInAs/GaAs VCSEL, modulation schemes, phased array VCSEL, Talbot cavity VCSEL, tunneling injection, tandem VCSEL, and so on [5],[6].

Some value-added technologies have been considered such as; continuous tuning, temperature insensitive wavelength (zero temperature coefficient), coherent array (Talbot cavity), MEMS integration, phased array, beam steering, high frequency modulation (>40GHz), hollow-waveguide integration (modulator/slow-light), and nearly unity spontaneous emission factor.

IV. PROSPECT

In Table I, we show possible application areas of VCSELs . The VCSEL itself is basically an exploratory device and generated Gigabit Ethernet and fiber channel applications[5]. It is emerging into higher class of data communication system such as 10 Gigabit Ethernet, high speed LAN's, optical interconnects, optical links, and so on. Moreover, long wavelength VCSELs have been developed toward long distance metropolitan area networks (MAN's). 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 '**Green ICE**' technology in various aspects by featuring low power and high speed performances. Optical interconnect of LSI chips and circuit boards and multiple fiber systems like in super-computers and PC's is the most interesting field related to VCSELs. Also, VCSEL-based photonics opened up various fields such as laser printers, computer mice, optical sensors, and so on. The arrayed microoptics technology [5] will be very useful for advanced systems.

The concept of VCSEL has been expanded into nano-photonics and photonic crystal field. The ultra-parallel and ultra-high speed photonics based upon sophisticated VCSELs including MEMS and integrated optics will open up a new era in this century.

Several extended applications have been considered; high power lasers, engine ignition, micro-power lasers, 3-color lasers, organic VCSEL (injection scheme and reflector), blue-green VCSEL, single photon VCSELs, and so on.

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Table I VCSEL Applications and Systems

Technical Fields	Applications and Systems
1. Optical Communications	**LANs, Optical links, Mobile links**
2. Computer Optics	**Computer link, Optical interconnects, High speed/Parallel data transfer**
3. Optical Memory	**CD, DVD, Near field, Multi-beam**
4. Optoelectronic Equipment	**Printer, Laser pointer, Mobile tools, Home appliances**
5. Information Processing	**Optical Parallel processors processing**
6. Optical Sensing	**Computer mouse, Fiber sensing, Bar code readers, Encoders**
7. Displays	**Array and surface light sources, High efficiency light-sources**
8. Illuminations	**Search-lights, Micro illuminators, Car's head lights**
9. Laser Machining	**Engine ignition, Manufacturing**

Kenichi Iga received the B.E., M.E., and Dr. Eng. degrees

from the Tokyo Institute of Technology, in 1963, 1965 and 1968, respectively. From 1968, he joined the P&I Lab., Tokyo Institute of Technology, became Associate Professor in 1974 and Professor in 1984. He retired Tokyo Institute of Technology in March 2001 and was awarded by Professor Emeritus. Dr. Iga joined Japan Society for the Promotion of Science (JSPS) as Executive Director from April 2001 to September 2007. He has been serving as the President of Tokyo Institute of Technology from October 2007 till September 2012. From 1979 to 1980, he stayed at Bell Laboratories as Visiting Technical Staff Member.

Dr. Iga first proposed and pioneered the research of surface emitting lasers and microoptics. He is one of the founders of Microoptics Conference.

Prof. Iga received 1992 IEEE/LEOS William Streifer Award, 2003 IEEE Daniel E. Noble Award, 2002 Rank Prize, 2001 Purple Ribbon Prize from the Emperor of Japan, 2003 Fujiwara Award, 2007 C&C Prize, and 2009 NHK Broadcast Cultural Award. In 2013, he was awarded by **Franklin Medal** with the Bower Award and Prize in Science.