Vertical Cavity Surface Emitting Laser (VCSEL) Technology

Gary W. Weasel, Jr. (gww44@msstate.edu)
ECE 6853, Section 01
Dr. Raymond Winton

Abstract
Vertical Cavity Surface Emitting Laser technology, typically constructed from GaAs material uses distributed Bragg Reflectors (DBRs) to sandwich an active region to create a vertical cavity achieving optical gain. While many variations of the technology exist, two gain structures, Uniform and Periodic, are briefly discussed. Additionally, a quick investigation into a particular technology referred to Tunable VCSEL is explored. VCSEL since its early research in the late 1970s has become an essential technology for much of today's commercial use.

1. Introduction

The Vertical Cavity Surface Emitting Laser (VCSEL) is a technology that has come to great importance in the optical communications field. From the time that researchers first developed the VCSEL to now with many different abilities and realizations of VCSEL available commercially today, VCSEL has made its use in many different current-technology applications.

VCSEL itself has become its own field, with a seemingly unending realm of possibilities and variations of the technology. Discussion in this paper aims to give a brief overview of the VCSEL technology and its field.

This paper begins by delving into the history of VCSEL and the accomplishments in the first decade of its research. Then the basic design and analysis of the VCSEL will be discussed, going into several different characteristics involved. Afterwards a brief view of current-day use will be given of VCSEL as it pertains to technologies they are used in and its manufacturing process.

2. History

The history of VCSEL research only spans the last three decades. Yet major achievements in the technology have been made over the years, especially after the point when VCSEL was being extensively studied.

2.1 Initial Research

The first ideas of the Vertical Cavity Surface Emitting Laser (VCSEL) were conceived in the late 1970s at the Tokyo Institute of Technology by Kenichi Iga and his colleagues. The device was first suggested in 1977, and in order to operate they indicated that VCSEL should have a very small cavity volume, high optical gain, and mirrors with a very high reflectively. At this time one of the major difficulties was acquiring a high gain using bulk materials and acquiring mirrors that would satisfy the needed reflectivity

Its first realization of VCSEL was achieved in 1979 where a 1300-nm wavelength GaInAsP-InP material was used for the active region. The operating temperature for this first device was at 77 K. It would be several years later when they reported GaAs/AlGaAs VCSEL pulsing at room temperature [2,6].

2.2 Accomplishments Over Years

Extensive research continued on VCSEL as in 1986 a GaAs VCSEL was created with only a 6-mA threshold. In 1988 the first room-temperature continuous wave (CW) GaAs VCSEL was created. Just a year later the threshold current again reduced to 1-2 mA in a GaInAs VCSEL device.

From that point on the rapid growth of GaAs VCSELs of many different wavelengths was supported by promising advances in optical materials, such as in the case where metal based

mirrors were eventually replaced by epitaxial grown mirrors, as in the case of distributed Bragg Reflectors (DBRs). Since 1992 VCSEL has undergone extensive studies and with more efficient optical materials available for VCSEL construction, threshold currents quickly entered the submilliampere range. The two noteworthy experiments improving the threshold current and demonstrating successful operation of a CW VCSEL device at room temperature encouraged others to starting entering the promising field of VCSEL research [2,6].

3. VCSEL Basics

What makes the VCSEL structure special is that it emits light perpendicular to the surface of the semiconductor. This makes more features available on VCSEL as compared to other conventional lasers [1]. Therefore, the structure of a VCSEL is significantly different from other laser structures have been seen so far, such as stripe lasers or edge-emitting lasers [6]. Because of this dramatic difference in the structure, the same design techniques of convention facet-emitting lasers cannot be applied. An example of this is seen in the concern of high-longitudinal side-mode suppression. In typical facet-emitting lasers, this is a great concern, but is completely disregarded in VCSEL design [2].

3.1 Simple Construction and Analysis

The construction of a VCSEL is particularly different from other lasers. VCSEL consists of a vertical cavity formed by epitaxial layers and employs a DBR above and below the active region. As witnessed in figure 3.1, light is taken from one of the DBR mirrors for the laser.
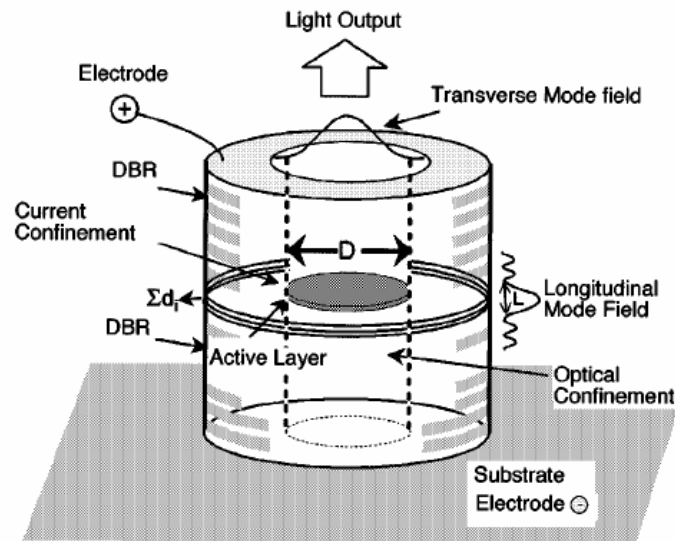

Figure 3.1 - Model of the Vertical Cavity Surface Emitting Laser [6]

The DBR mirrors are highly reflective mirrors, with a reflectivity of greater than 99.9%. The mirrors can be either epitaxial growth or dielectric multilayered [2]. The two DBRs in the VCSEL are oppositely doped (n-DBR and p-DBR). Placed between the upper and lower DBRs is an active region emitting light, usually containing several quantum wells. The active region

receives current through a current-guiding structure by either proton-injected surroundings or through an oxide aperture.

In figure 3.2 we find an example of a three-wavelength VCSEL array. One of the key features of VCSEL is the ability to integrate multiple VCSELs together into a one or two dimensional array, therefore giving lasers of multiple wavelengths together [1].
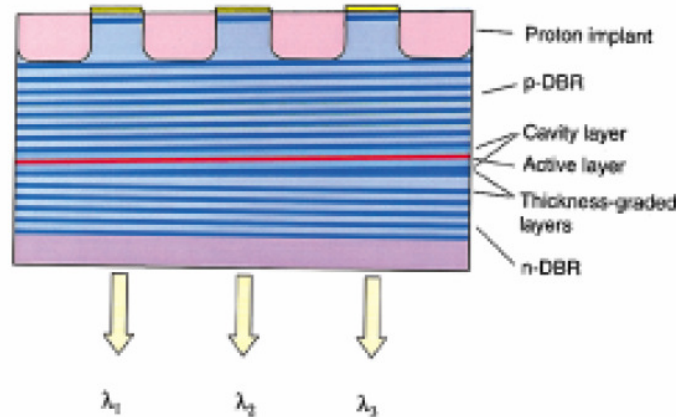

Figure 3.2 - Three-Wavelength VCSEL Array

To engineer a particular wavelength in VCSEL, one method used is the thickness-gradient placed in the DBR under the active region. This creates a different cavity thickness across the structure, as seen, for example, in Figure 3.2 with the thickness-graded layers becoming thicker from left to right [4].

3.2 Gain Structures

Inside of a VCSEL there are different types of gain structures that can be used to optimize both the threshold current density and differential quantum efficiency. The threshold current density is a particular current that defines when the gain inside the laser is equal to the loss, between the lasing and non-lasing thresholds. Differential quantum efficiency refers to the rate of the number of protons emitting from the active region to the number of electrons enforced by an electrical charge [7].

One type of gain structure is a Uniform Gain Structure (UGS). In a UGS, an active layer is placed between two confinement layers with mirrors on the ends of the structure. The confinement layers are n- and p-doped. The mirrors provide feedback to the active region which is then amplified. A carrier concentration injected into the active region facilitates stimulated emission. This structure is seen below in Figure 3.3
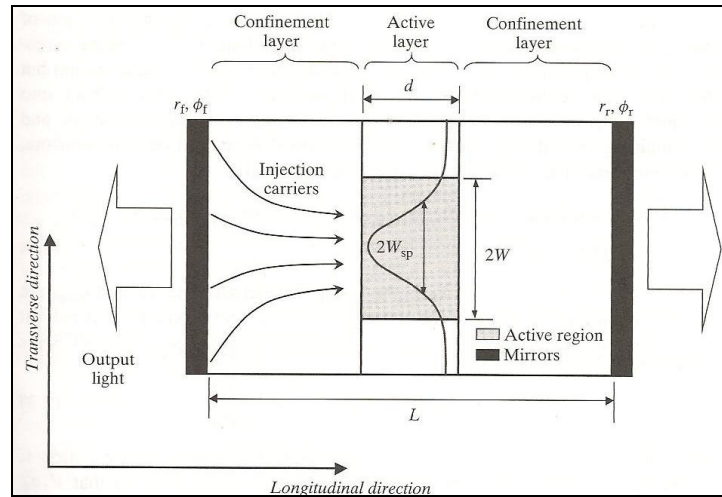
Figure 3.3 - Model of Uniform Gain Structure (UGS) [2]

A second type of gain structure is the Periodic Gain Structure (PGS). As shown in figure 3.4, the PGS employs multiple active regions that are at the peak of the wavelength emitted to perform a gain with the period of the light wave. This structure improves the performance of VCSEL by maximizing the overlap occurring between standing-wave peaks and the gain medium. The various active regions positioned at the peaks of the standing-waves are at a distance of $\lambda_R/2n$ apart, where λ_R is the lasing wavelength.
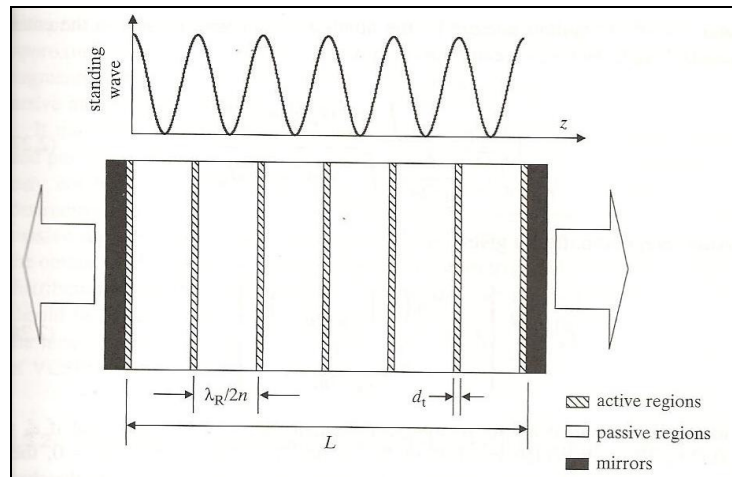

Figure 3.4 - Model of Periodic Gain Structure (PGS) [2]

There are other advantages of the PGS over the UGS. One advantage is because the gain medium aligns with the peaks of the standing-wave pattern, it is difficult to have longitudinal spatial hole burning. PGS also makes longitudinal mode operation favorable since the gain medium is anisotropic and wavelength-selective. The threshold current is also anticipated to decreased by half when using a PGS compared to a UGS [2].

4. Tunable VCSEL

To provide a more in-depth feel of a particular VCSEL technology, the Tunable VCSEL developed is investigated briefly in the following sections.

4.1 Laser Structure

The tunable VCSEL structure is referred to as cantilever-VCSEL (c-VCSEL) due to the additional structure added to the typical VCSEL. Figure 4.1 shows a schematic of the c-VCSEL structure. The c-VCSEL differs by using an extra top-layer of n-doped DBRs above the p-doped DBRs covering the active region. Between the n-doped DBR and p-doped DBR of the "top mirror" is an air gap, above which contains a freely suspended cantilever structure directly above the laser output.
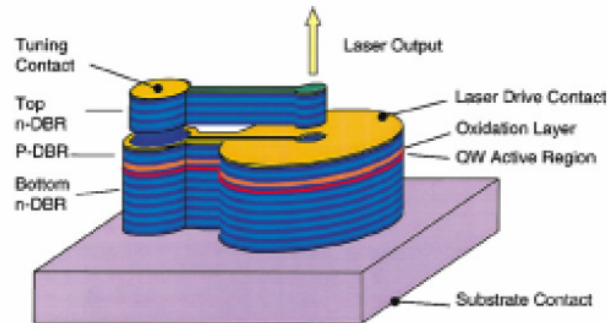

Figure 4.1 - cantilever-VCSEL (Tunable) Schematic [4]

One of the most important parts of c-VCSEL fabrication is the formation of the cantilever. Selective etching of GaAs against AlGaAs is performed in this fabrication step. Figure 4.2 below shows SEM photos of a successfully constructed cantilever structure in a c-VCSEL.
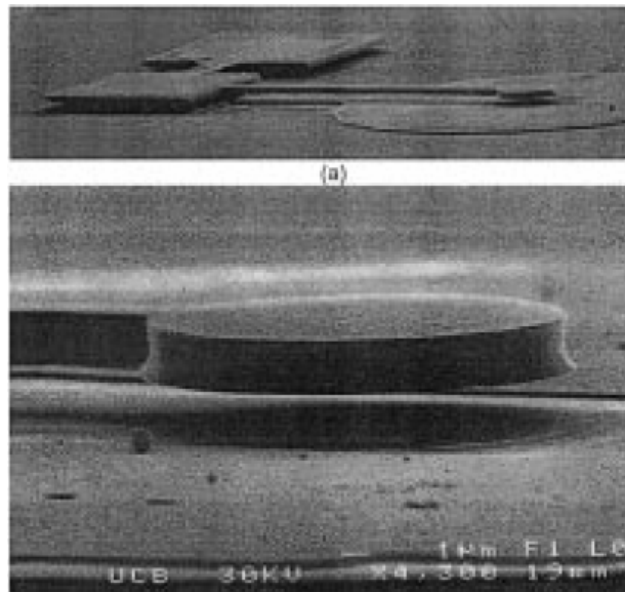

Figure 4.2 - SEM Photo of a c-VCSEL device [4]

In this photo the length of the cantilever is 100 μm, and its width and thickness is 3 μm. The headpiece of the cantilever has a diameter of 10 μm with the air gap underneath it only 1.4 μm thick [4].

4.2 Tuning Mechanism

The tuning mechanism to vary the wavelength emitted by the c-VCSEL is utilized by application a voltage across the airgap (between the n-doped DBR and p-doped DBR). A reverse bias voltage attracts the cantilever closer to the substrate and therefore decreases the length of the airgap. Consequently the laser wavelength is tuned toward a shorter wave-length.

To determine the available range at which a particular c-VCSEL can be tuned, three factors chiefly affect this range: the gain or DBR bandwidth, the difference of the wavelength noted at the maximum deflection of the cantilever, and minimum free spectral range (FSR). In addition to these factors is the mechanical maximum deflection of the cantilever and capacitance across the airgap.

An approximation for maximum deflection of the cantilever (approximately 1/3 the airgap) is given below:

$$z = \frac{\pi r^2 \varepsilon}{E} \frac{2l^3}{wt^3} \frac{V^2}{(d-z)^2} \tag{4.1}$$

Here d is airgap width without an applied voltage, z is the cantilever displacement with an applied voltage, V is the voltage being applied across the airgap, E is the bulk modulus, and r, l, w, and t are respectively the radius, length, width, and thickness of the cantilever.

An experiment of c-VCSEL shows a tuning range of 31.6 nm centered at 950nm. The power required to perform the tuning since hardly any current flows through the junction resides in the range of 100 nW to 1 microwatt. Additionally tuning speed (typically falling from 1 to 10ms) is also investigated, and is affected by the properties of the cantilever, much like the maximum deflection of the cantilever [4]. An approximate estimate is given by the following equation:

$$\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{Ewt^3}{2l^3 m}} \tag{4.2}$$

5. VCSEL Today

Whether people realize it not, VCSELs are an integral part of technology today. The many advancements that VCSEL technology has made in just a few short decades has brought them fully into commercialization and into many of the products that are being bought every day.

5.1 Commercialization and Manufacturing

After extensive research of VCSEL went underway, it was not long before the first commercialized version was reached. In 1997 rapid development of GaAs-based lasers established the short-wavelength VCSEL (i.e., 850-980 nm) into the commercial market.

With the commercialization of VCSELs starting in 1997, it dominated the market of many high-speed local area network technologies available. One of the largest advantages to VCSEL is the simplicity of device testing, since VCSELs can be tested on the wafer before it is even cut. Other advantages bolstering its dominance are narrow beam divergence, a low current requirement, easy polarization control, and stable single-mode operation. More than a dozen manufacturers are currently production short-wavelength VCSELs. In their products are included single-diode packages, arrays, and data communication systems [2].

5.2 Current-Day Use

One of the most difficult attributes of commercializing VCSEL is the need for reliability. One of VCSELs uses today includes transoceanic optical fiber communication systems, which should not require ship repairs more than three times over the course of 25 years. VCSELs with an oxide aperture have a longer lifetime than those that are ion implanted. However, ion implanted VCSELs have reached an acceptable reliability for the tradeoff of cheaper cost. Both today are found in wide, metro, and local area networks in gigabit Ethernet.

Other current-day VCSEL use is in computer networks, printing, display systems, optical sensing, high-density optical storage, and optical information processing [2].

6. Conclusion

The Vertical Cavity Surface Emitting Laser has come long strides in the short time of its existence. Seemingly countless more variations of the technology go beyond the scope of this paper and are still continuously being researched. The low threshold current for VCSELs has become particularly attractive (currently 10-100 µA) and the target of threshold current research is 1 µA [6]. The commercialization of GaAs VCSELs has produced many of the technologies available to us today and assists in keeping the world connected.

References

[1] G Keiser, *Optical Fiber Communications*, 4th ed. McGraw-Hill, New York, NY, 2011

[2] S. F. Yu, *Analysis and Design of Vertical Cavity Surface Emitting Lasers*, Wiley, Hoboken, NJ, 2003

[3] Hongling Rao, M. J. Steel, R. Scarmozzino, and R. M. Osgood Jr., "VCSEL design using the bidirectional beam-propagation method," *IEEE Journal of Quantum Electronrics*, vol. 37, no. 11, pp. 1435-1440, Nov. 2001.

[4] C. J. Chang-Hasnain, "Tunable VCSEL," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 6, no. 6, pp. 978-987, Nov.-Dec. 2000.

[5] H. C. Kuo, Y. H. Chang, Y.-A. Cahgn, F.-I. Lai, J. T. Chu, M. Y. Tsai, S. C. Wang, "Single-Mode 1.27-µm InGaAs:Sb-GaAs-GaAsP Quantum Well Vertical Cavity Surface Emitting

Lasers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 11, no. 1, pp. 121-126, Jan.-Feb. 2005.

[6] K. Iga, "Surface-Emitting Laser – Its Birth and Generation of New Optoelectronics Field," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 6, no. 6, pp. 1201-1215, Nov.-Dec. 2000.

[7] M. H. Weik, *Fiber Optics Standard Dictionary*, 3rd ed. Chapman & Hall, New York, NY, 1997.