Vertical Cavity Surface Emitting Lasers in Data Networks and Consumer Devices

Jim A. Tatum

Finisar, 600 Millennium Drive, Allen, TX 75013
e-mail: Jim.Tatum@Finisar.com Phone: (214) 509-2808

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Abstract

Vertical Cavity Surface Emitting Lasers (VCSELs) were first commercialized in 1996 by Honeywell and were primarily deployed in data communications networks, and since then have been used in several consumer devices. Today, VCSELs are commercially available at wavelengths ranging from 670 nm to nearly 2 µm, and powers ranging from a few microwatts to more than 10 W in a single chip. It is estimated that more than 1B VCSELs have been shipped by several suppliers. This paper presents a brief history of VCSELs and describes some of the future applications.

INTRODUCTION

In the past 20 years, there have been many changes in the VCSEL industry [1]. Interestingly, none of the original manufacturers of VCSELs have the same company name, but many of the original personnel remain. Many were sold, some closed, and others caught in corporate restructuring. Two companies, Finisar and Avago (now Foxconn and Broadcom Limited), are the leading manufacturers of VCSELs for the data communications market due to vertical integration to the optical transceiver. The commercial market volume, mostly optical navigation devices, has been driven primarily by Philips and II-VI. Other specialty applications exist, such as atomic clocks, oxygen sensors and precision optical encoders, though the volumes on these components have been historically small. Figure 1 shows the market segmentation, representative products and annualized volumes that will be described in the following sections.

DATA COMMUNICATIONS MARKET OVERVIEW

Commercial adoption of VCSELs was driven by the adoption of IEEE 802.3z (Gigabit Ethernet) and Fibre Channel ANSI X3.T11 standards. VCSELs represented a significant improvement in laser reliability, speed, cost, power consumption, and component manufacturability when compared to edge emitting lasers at similar wavelengths. These lasers were manufactured using implant technology to define the emitting area, and operated at speeds of 1 Gbps. Since then, VCSELs have migrated to emission apertures defined by wet oxidation, and speeds have evolved to more than 28 Gbps [1].

Looking forward, the data communications market for VCSELs will continue to grow. At 28 Gbps, the highest commercial speed available today, optical interconnect cables are beginning to replace copper cabling for even the shortest interconnects within the data center. This could represent a 10x increase in the available market. The next speed increment may be the first time that the fundamental speed of the laser is not sufficient, and adoption of other communication protocols such as pulse amplitude modulation (PAM) and integration of link equalization. These techniques,

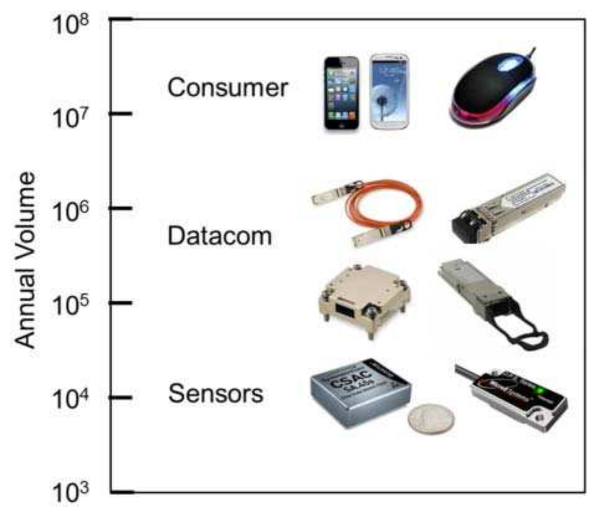

Figure 1. Overview of the VCSEL market segments and annual volume and representative end products in each segment.

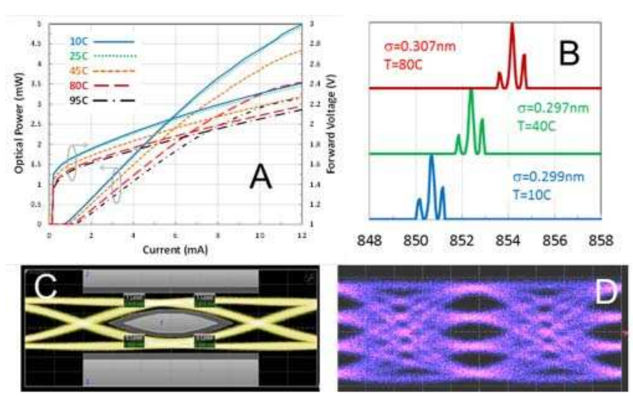

Figure 2. (A) Light output and voltage as a function of drive current and temperature, (B) Optical spectrum at 8 mA, (C) Optical eye diagram at 28 Gbps, (D) Optical eye diagram of a PAM4 28GBd VCSEL (56 Gbps).

while new to the VCSEL market, are ubiquitous in copper based interconnects. Standards are now being written for single channel speeds of 56Gbps using PAM4 signaling. This places new requirements on the laser for linearity and extremely low Relative Intensity Noise (RIN). Figure 2 shows typical performance of a production 28 Gbps VCSEL.

Recently Finisar has introduced a Short Wavelength Division Multiplexed (SWDM) product line that utilizes four VCSELs operating at 850, 880, 910 and 940 nm [2]. The SWDM solution offers an extension of the life of installed multimode optical fiber (MMF) by allowing up to 100 Gbps on a single fiber. To date, 100 Gbps on MMF required parallel fiber cabling. SWDM represents a significant cost savings and extended utilization of MMF in the data center, and reduces the amount of parallel fiber connectors.

CONSUMER MARKET OVERVIEW

In the consumer market, VCSELs first appeared in optical navigation devices in 2000, aimed at the high end user such as gamers. Today, VCSELs can be found in even the lowest cost components. The optical navigation market has been in decline over the last several years due to rapid adoption of touch screens and the increasingly mobile computer environment. However, the adoption of VCSELs into new applications within laptops, tablets and cell phones is now emerging [3]. VCSELs have been demonstrated in applications such as (1) autofocusing, (2) proximity sensing, (3) video signaling to the display and camera, (4) low noise microphones, and (5) gesture recognition. The adoption is being driven by the very low power consumption compared to LEDs and other packaging considerations that limit signal integrity of electronic components.

High power VCSEL emitters, such as those used in gesture recognition, represent a significant departure from traditional VCSEL applications. Previously, VCSELs were utilized with a single emitting element in each die. In high power devices, the emitters are arranged in a two dimensional pattern, and each die may contain hundreds of individual emitting elements connected in parallel. This configuration has significant technical advantages over edge emitting lasers. First, the optical power density at each of the elements is relatively low, therefore facet damage and hence likelihood of device failure is very much reduced. Second, with a large number of emitters, there is inherent redundancy in the emitter. For example, in a time of flight gesture recognition system, failure of a single emitter would represent <1% change in the total power output of the array, and would not affect the optical beam profile, making the system fault tolerant. Similarly in triangulation based gesture recognition, a single failure in an array can be calibrated or interpolated out using signal processing, thereby making the device fault tolerant. Figure 3 shows the difference between a single emitting VCSEL and a typical two dimensional array.

Two dimensional arrays of emitters are also being utilized in a variety of other systems such as night vision or stealth illumination [4]. In fact some of the original development work on high power VCSELs was driven by DARPA contracts. Systems with many kilowatts of optical power have been demonstrated in military applications. Commercial interest has centered on illumination for security cameras that can be made more discrete (not visible to the human eye), and in computer vision illumination such as parking spot sensors.

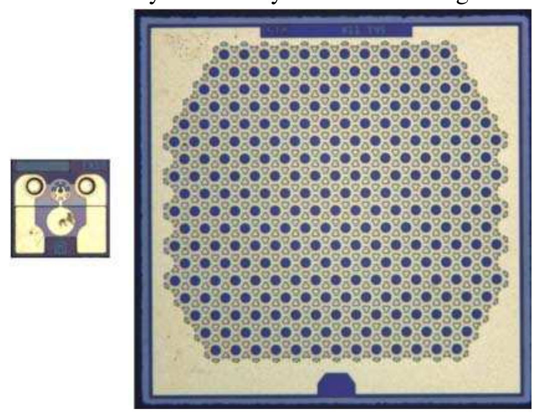

Figure 3. Image of standard 28G VCSEL (left) and a high power VCSEL array (right) shown at approximately proportional die sizes.

Yet another application for these high power arrays is in thermal processing of materials in a production line [3]. Systems with more than 5kW of optical power have been implemented. The significance of these sources is that a single unit may contain more than 500,000 individual emitters, or the equivalent of an entire 100 mm wafer of densely packed VCSELs. Some system design may require 10 MW of total optical energy, and therefore consume more than 1000 100 mm wafers of VCSELs in each implementation. These high emitter count applications have

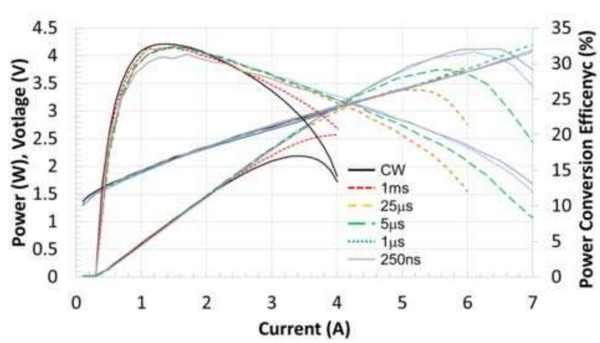

Figure 4. Power, voltage and PCE as a function of drive current for several different electrical driving conditions. Duty cycle approximately 10%.

the potential to significantly increase the number of VCSEL wafers produced annually.

Figure 4 is a plot of a typical high power VCSEL array with several different electrical drive conditions. When operated below the thermal time constant of the VCSEL active region (~1 µs) significantly higher peak powers can be obtained. It is important to understand how the laser characteristics change under the various potential operating conditions. For example, some applications may require CW or quasi-CW operation, such as triangulation based gesture recognition, whereas time of flight techniques utilize more narrow pulse widths. High peak powers are also particularly attractive for LIDAR applications in the automotive industry. The operating point for the laser is one of the most important parameters in designing two dimensional arrays. The power conversion efficiency, PCE, is another important design consideration and requires the trade-off between the laser resistance and slope efficiency. At high operating currents, beyond the peak PCE point, will decline inversely proportional to the resistance. These are the most salient point in optimizing the die size, and therefore cost, for a given application.

SENSOR MARKET OVERVIEW

The sensor market can be sub-segmented into two categories depending on potential volume. The lower volume applications (<100 k/yr) include optical encoders, oxygen sensors, and atomic clocks. These generally demand single polarization stable modes and precision wavelengths to operate. Figure 5 shows the light output of the two polarization modes and the polarization extinction ratio of a typical VCSEL used in these applications. The large volume segments are being driven by applications in consumer electronics as discussed earlier. Here the focus is on cost and simplicity, driving die sizes to under 0.02 mm^2 and yielding more than 200,000 elements on a single 100 mm wafer.

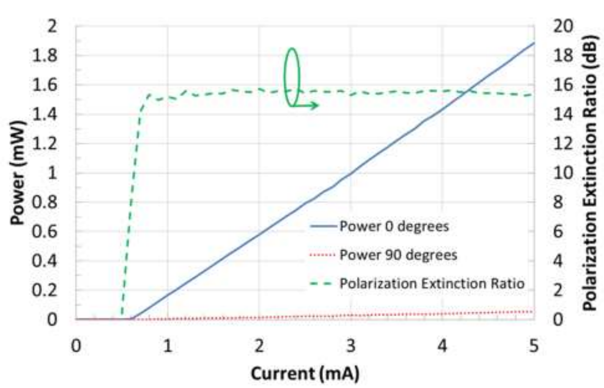

Figure 5. Light output and polarization extinction ratio of a single mode VCSEL.

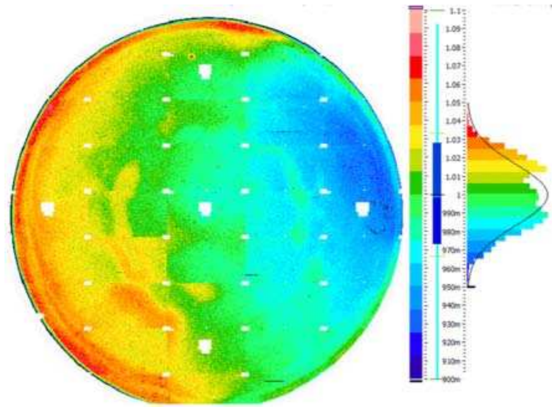

Figure 6. Normalized power map for a 4-inch VCSEL wafer with more than 200,000 good VCSELs. The total power range is +/- 5%.

Figure 6 demonstrates a typical wafer map of a sensor market VCSEL showing the normalized optical power across a four inch wafer. The total range is +/- 5% with more than 200,000 VCSELs tested. The black streaks on the top of the wafer are a result of dirty probes. While these applications do drive significant device counts, the die size will have only a marginal impact on the total number of processed wafers.

FUTURE VCSEL MANUFACTURING REQUIREMENTS

To date, the VCSEL industry has been relatively small when compared to LED and RF IC manufacturing volume. The main players have been specialized laser fabs with a focus on diversity of processes and capability required by the several unique device characteristics in a potential application. For example, high speed devices may require very low capacitance and control of AC performance. This drives a unique set of tools and test equipment. Similarly, for single mode and sensor applications, mode control and wavelength control are paramount, which drive different fab and test requirements. Future integration of lens, backside processing, and metal plating will drive further diversity in the fab operations. This diversity has enabled the optical sensor and data communications industry. The ability to effective manage the supply chain to provide rapid feedback of reliability, test yields and in process yields to the operation has been critical to VCSEL manufacturing. These smaller fabs have often operated in relatively low wafer volume and high complexity, both of which have made the outsource manufacturing of VCSELs unattractive. With the potential of increased wafer volume being presented to the compound semiconductor industry, several foundry and epitaxial service companies have begun to show interest in the VCSEL market [5]. Among these was Anadigics, which has recently been the subject of several acquisition targets by both RFIC and VCSEL companies, which underscores the potential move to higher wafer volumes.

Comparison of VCSEL and RF IC Manufacturing

When compared to the manufacturing volumes of GaAs based RF ICs and associated devices, the number of VCSEL wafers produced annually seems almost insignificant. It is estimated that more than 10,000 150 mm wafers are produced every week by the several RF IC suppliers. Conversely, VCSELs are generally manufactured today on 3 inch substrates and is estimated to be much less than 500 wafers per week. When normalized to substrate area, VCSELs represent approximately 1% of the GaAs material processed. Another way to compare RF ICs and VCSELs is device area, where most RF ICs approach and often exceed 1 mm^2, whereas single VCSELs can be less than 0.025 mm^2 and have more than 100,000 components on a single three-inch wafer.

The epitaxial wafers for both VCSELs and RF ICs are generally grown by Metal Organic Chemical Vapor Deposition (MOCVD), though the use of Molecular Beam Epitaxy (MBE) is also used. RF ICs typically contain less than 10 discrete epitaxial layers representing approximately 3 µm of deposition. In contrast, VCSELs may contain more than 100 discrete layers and about 10 µm of deposited material. Additionally, the materials required for the VCSEL result in highly strained epi wafers, which does present certain manufacturing challenges in fabrication. RF ICs typically have about 15 mask levels to define the circuits, while VCSELs can be made with as few as 5 mask steps. Most VCSEL manufacturers are considering a transition to 100 mm wafers, and some potentially moving to 150 mm wafers. Scaling to larger wafer diameters will hold several manufacturing challenges, particularly in uniformity of the emitting aperture formed by wet oxidation, and epitaxial uniformity. This transition is being driven by anticipation of a major increase in the use of large 2 dimensional arrays of VCSELs in high power systems.

Conclusions

In the coming years, VCSELs will continue to be the workhorse of the data center and grow into even more consumer and specialty products. The total number of VCSELs manufactured is expected to continue to grow as existing markets expand. New applications are beginning to emerge that have the potential to significantly grow the industry, however the total number of wafers processed will continue to be a small fraction of the RF IC industry.

Acknowledgements

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Acronyms

VCSEL: Vertical Cavity Surface Emitting Laser
MOCVD: Metal Organic Chemical Vapor Deposition
Gbps: Gigabit per second
GBd: Gigabaud
PAM: Pulse Amplitude Modulation
MBE: Molecular Beam Epitaxy
RF IC: Radio Frequency Integrated Circuit
LED: Light Emitting Diode
IEEE: Institute of Electrical and Electronic Engineers
DARPA: Defense Advanced Research Projects Agency
LIDAR: Light Detection and Ranging
PCE: Power Conversion Efficiency
RIN: Relative Intensity Noise