# VCSEL technology for medical diagnostics and therapeutics

M.K. Hibbs-Brenner*[a], K.L. Johnson[a] , M. Bendett[b]
[a]Vixar, 15350 25th Ave N, Suite 110, Plymouth MN, USA 55447;
[b]Lockheed Martin Aculight, 22121 20th Ave SE, Bothell, WA USA 98021

## ABSTRACT

In the 1990's a new laser technology, Vertical Cavity Surface Emitting Lasers, or VCSELs, emerged and transformed the data communication industry. The combination of performance characteristics, reliability and performance/cost ratio allowed high data rate communication to occur over short distances at a commercially viable price. VCSELs have not been widely used outside of this application space, but with the development of new attributes, such as a wider range of available wavelengths, the demonstration of arrays of VCSELs on a single chip, and a variety of package form factors, VCSELs can have a significant impact on medical diagnostic and therapeutic applications.

One area of potential application is neurostimulation. Researchers have previously demonstrated the feasibility of using 1850nm light for nerve stimulation. The ability to create an array of VCSELs emitting at this wavelength would allow significantly improved spatial resolution, and multiple parallel channels of stimulation. For instance, 2D arrays of 100 lasers or more can be integrated on a single chip less than 2mm on a side. A second area of interest is non-invasive sensing. Performance attributes such as the narrow spectral width, low power consumption, and packaging flexibility open up new possibilities in non-invasive and/or continuous sensing. This paper will suggest ways in which VCSELs can be implemented within these application areas, and the advantages provided by the unique performance characteristics of the VCSEL. The status of VCSEL technology as a function of available wavelength and array size and form factors will be summarized.

**Keywords:** VCSEL, Vertical Cavity Surface Emitting Laser, neurostimulation, biomedical sensor, near infra-red, red

## 1. INTRODUCTION

VCSELs, or Vertical Cavity Surface Emitting Lasers are a relatively recent entrant to the list of choices of semiconductor light-emitting devices. Figure 1 is a schematic that illustrates some of the differences in the characteristics and the structure of VCSELs compared to two other commonly used optical sources – the light-emitting diode (or LED) and the edge-emitting laser (which we will refer to as an EEL).

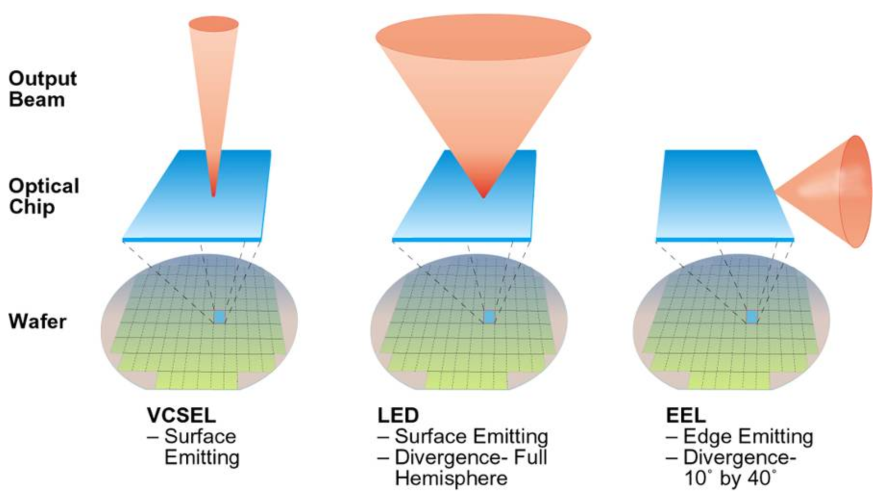


**Figure 1**. Comparison of the structure and characteristics of three common semiconductor light emitters.

All three types of semiconductor devices are fabricated by growing epitaxial III-V semiconductor layers (such as GaAs, AlGaAs, InP, or InGaAsP) on a GaAs or InP substrate. A diode is created by including a p-n junction in the epitaxially grown layers. The wafers are processed through several photolithographic steps to define the individual devices, such as etching ridges, depositing and patterning metal contacts, or depositing and patterning dielectrics. The LEDs typically emit light from the top surface of the wafer, and so devices can be tested at the wafer level by probing bond pads accessible at the surface of the wafer. Lasers, however, require a feedback mechanism, implemented with mirrors sandwiching the gain region. In a conventional laser this is achieved by cleaving the wafer, and the cleaved edges form the parallel mirrors of the device, resulting in light emission from the cleaved edge of the wafer. Unfortunately the devices can not be tested until the wafers are broken into individual lasers or laser bars. VCSELs development accelerated when researchers realized that mirrors with sufficient reflectivity could be grown or deposited on the wafers, sandwiching an active region. This results in vertical emission from the wafer, and, as in the LED case, allows the devices to be tested at the wafer level.

In addition to the manufacturing advantages of wafer scale testing there are a number of performance advantages to VCSELs as compared to either LEDs or low cost EELs. These include lower power consumption, the ability to easily create 1-D and 2-D arrays of lasers on a single chip, a symmetric optical beam with a narrow beam divergence, narrow spectral width, and the compatibility with a wide variety of package types including surface mount lead frame packages and chip on board. The details of the performance and the implications for medical applications will be discussed in more detail below.

The first report of a Vertical Cavity Laser was published by Prof. Iga's group from Tokyo University in 1979.[[1]] This device used dielectric layers to form the mirrors and emitted light at 1300nm, but only operated when cooled below room temperature. VCSEL research really took off in the mid- to late 1980's when researchers realized that the mirrors could be epitaxially grown in the AlGaAs materials system for devices emitting at a wavelength near 850nm.[2,3,4,5,6]

Almost all of the early research and development on VCSELs was carried out at either 850nm or 980nm because that wavelength range combined the wavelength region of interest for fiber optic communications with wavelengths that were the simplest to implement technically. VCSELs for short distance communications such as Local Area Networks (LANs) and Storage Area Networks (SANs) have been in full scale production since the late 1990's[[7]] and more than 50 million VCSELs have been shipped by Honeywell/Finisar alone.[[8]] However, since the mid 1900's VCSELs with wavelengths covering a wide range have been demonstrated, including 670nm[[9],[10]], 780nm[[11]], 1300nm[[12],[13]], and 1550nm[[14]].

## 2. MEDICAL APPLICATIONS AND REQUIREMENTS

### 2.1 Sensing applications

Pulse oximetry, tissue oximetry and fluorescence based biomarker sensors are some of the sensing applications that can benefit from the availability of VCSELs in an expanded wavelength range.

Pulse oximetry has long relied on the application of light emitting diodes.[[15]] The wavelengths of interest are in the red (660nm) and infra-red (850nm to 910nm). The ratio of the absorption of the light at the two wavelengths is used to calculate the oxygenation of the blood, and the correlation of the signal to the pulse is used to separate the signal of the arterial blood from venous and capillary blood. Sensors, which can be semi-durable, or disposable, consist of two LEDs and a photodetector, and are electrically connected via a cable to a signal processing system. A disadvantage of the cabling is that it often impedes the mobility of the patient.

More recently the technique has been expanded to the measurement of other blood gases such as carboxyhemoglobin and methemoglobin,[[16]]. Methemoglobin is a dysfunctional form of hemoglobin that is incapable of transporting oxygen, and hence can result in tissue hypoxemia. Carboxyhemoglobin results from carbon monoxide poisoning. Another variation of the technique is involves the measurement of the perfusion and oxygenation of tissue.[[17],[18],[19]] This differs from pulse oximetry in that, instead of just measuring the oxygenation of arterial blood, the blood in the tissue is a combination of arterial, venous and capillary blood. The level of tissue oxygenation provides valuable information to health care providers regarding the onset of shock in trauma situations, the potential for cerebral oxygen deprivation during heart surgery, or the occurrence of blood clots following plastic or reconstructive surgery.

Many of the new approaches to extending oximetry to dyshemoglobins or to tissue have involved increasing the number of wavelengths of light used in the sensors, from as little as three to as many as twelve, covering the range from the red to the near-infrared. LEDs have remained the preferred implementation due to their cost and convenient package form factors, such as plastic surface mount lead frame packages.

For all of these oximetry applications VCSELs provide the benefits of a narrower spectral linewidth emission, a 4X smaller shift in wavelength with temperature, and as much as an order of magnitude reduction in power consumption. The latter consideration is particularly relevant for a shift to wireless sensors for convenience of the patient or home monitoring of patients with telemetric medicine.

A more speculative area of application for VCSELs within medical sensing would be to the monitoring of biomarkers. A great deal of research is currently on-going in protein markers as indicators for diagnosis of disease and disease progression, for detection of medical crisis events, for regulation of treatment, or as indicators of the effectiveness of treatment. For example, biomarker proteins which indicate the occurrence of acute myocardial infarction are measured by point of care instruments such as the Biosite triage cardiac panel or Response Biomedical RAMP.[[20],[21]] The effectiveness of chemotherapy can be estimated by measuring the progression of apoptosis, or cell death, by measuring caspase activity, a protein released into the blood stream upon cell death.[[22]] These measurements are made by using an appropriate probe conjugated to a fluorescent dye. The probe binds to the measurand of interest, if present. When excited with the proper wavelength of light, the dye will fluoresce indicating the presence of the biomarker. While a central laboratory instrument can use nearly any kind of laser regardless of size or power consumption, point of care devices require small, power efficient sources. The fluorescent mechanism benefits from the narrow spectral width of a laser which minimizes the amount of light lost to filtering and enables the excitation and emission wavelengths to be more closely spaced. The more directional optical beam also results in more efficient use of the light, and a reduction in noise due to scattering of lost light. The high speed of a VCSEL compared to an LED allows for improvement in signal quality through time resolved measurements.

### 2.2 Neurostimulation applications

Neural prostheses are artificial devices that restore or supplement nervous system function that is lost due to diseases or disability. The ability to electrically stimulate nerves has been known and investigated for more than 200 years.[[23,24,25]] Although there has been success in the use of electrical stimulation in research and in neural prostheses, the method and benefits are limited by issues related to the electrode-tissue interface. The tissue can be damaged by high current levels or chemical reactions.[[26,27,28]] The spatial resolution achievable with electric stimulation is limited by the spread of current in the tissue.[[29,30]]

Scientists have also pursued mechanical methods of stimulation, including ultrasound and magnetic energy.[[31,32]] A technological breakthrough took place at Vanderbilt University where it was discovered that low levels of pulsed infrared laser light can reliably elicit neural action potentials in a non-contact manner.[[33]] As a result of this work, team members at Northwestern University realized the possible impact of the technology for cochlear implants.[[34,35]] When developed this will lead to cochlear implants with superior hearing fidelity and intelligibility by increasing the number of frequency bands that can be used simultaneously. The non-contact nature of the approach also has the advantage of preserving residual hearing, since the light shines through the round window of the cochlea. Similarly optical stimulation allows for precise stimulation of particular nerves within closely spaced nerve bundles. In contrast, electrical stimulation stimulates multiple nerves at the same time due to electrical cross-talk.

The remaining issue, however, is the implementation of this prosthetic approach in a format that allows for the miniaturization of multiple optical channels to a size that can be implanted. VCSELs (Vertical Cavity Surface Emitting Lasers) are suggested as a key technology that enables a cochlear or vestibular prosthesis to be achieved.

Studies have been carried out to understand the laser performance parameters required for this application.[[36]] As a result of this work, a preliminary set of specifications has been developed, and is supplied in Table 1 below. Some of the key parameters include the wavelength and wavelength range (XXX nm ± 10nm), the array size (on the order of 100 channels), and the peak output power (>20mW). The device should achieve these performance parameters at the typical body temperature.

**Table 1**. Preliminary performance requirements for long wavelength VCSEL arrays for cochlear and vestibular implants.

| Parameter | Units | Value | Tolerance | Comments |
|---|---|---|---|---|
| Laser array size | | 10 x 10 | NA | For evaluating uniformity |
| Wavelength | nm | TBD | ± 10 | Center value depends on targeted nerve type |
| Peak output power | mW | >20 | | For pulse widths from 10µsec to 1msec and repetition rates from 0 to 300Hz |
| Operating range | °C | 20-45 | | Determined by use at temperatures from room temperature to body temperature |
| Drive current | mA | <30mA | | For 10mW output power |

Of the three types of miniaturized optical sources available, Light-Emitting Diodes (LEDs), edge-emitting lasers (EELs) and VCSELs, VCSELs provide the unique combination of narrow spectrum, power conversion efficiency, and the ability to integrate into large arrays on a single chip. For instance, Vixar has demonstrated the ability to integrate an 8x8 array on a chip that is 1.5mm on a side at 670nm[[37]]. However, challenges remain to simultaneously meet all of the required performance specs simultaneously. In the next section we will illustrate some of the VCSEL capabilities which have already been demonstrated at Vixar.

## 3. DEMONSTRATED VCSEL PERFORMANCE

As summarized above, characteristics of interest for sensing and neurostimulation applications include the efficiency of the devices in converting electrical power to optical power, the ability to create arrays, the available packaging formats of the devices, the spectral characteristics of the lasers, and the modulation characteristics of the devices.

Figure 2 illustrates the power conversion efficiency of lasers at three different wavelengths located within the “therapeutic window” i.e. the spectral region in which the body is relatively transparent. The wavelengths illustrated are at 670nm, 795nm and 850nm. The light output and voltage versus the current through the laser is shown in each plot, and the power conversion efficiencies are indicated.

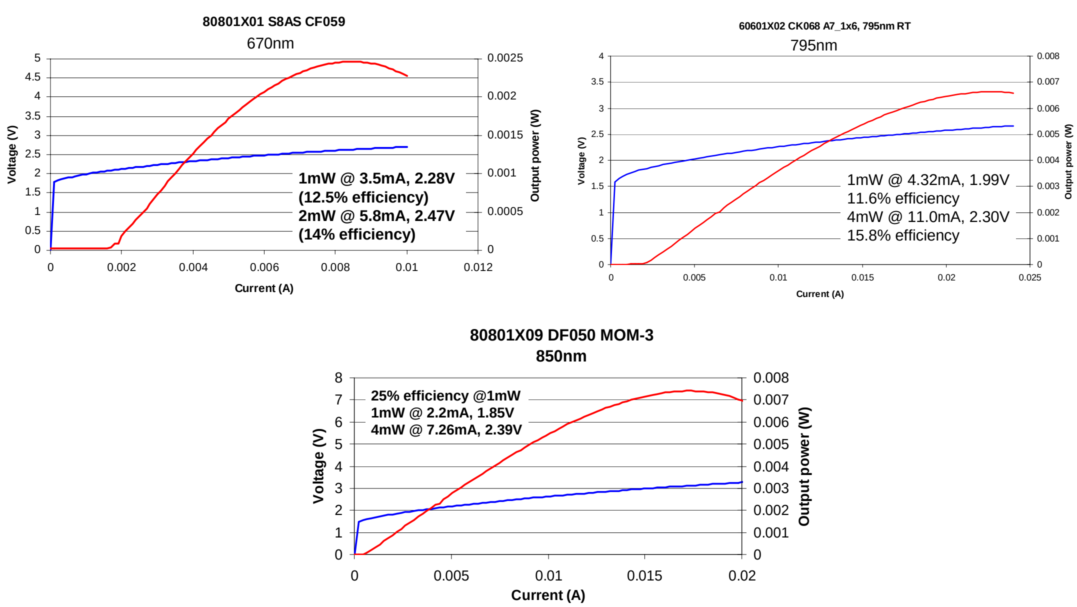


**Figure 2**. Light output and voltage versus current for three different wavelengths of VCSEL designed by Vixar: 670nm, 795nm and 850nm. The power conversion efficiency ranges from around 12% to 25%.

Sensing applications typically require approximately 1mW of output power. While a drive current in the range of 2.5-4mA is required to achieve the 1mW output power level for the VCSELs shown above, an LED commonly used for these applications can require 50mA or more current to achieve the same output power.

The spectral bandwidth of a single-mode and multi-mode VCSEL are shown in Figure 2. Single mode VCSELs have a Gaussian shape to the output beam profile and a very narrow spectrum (<0.2nm linewidth shown is limited by our equipment). A multi-mode device still has a narrow beam divergence and narrow spectrum (around 0.5nm) but the beam shape is not Gaussian. The single mode devices are preferable for applications requiring high beam quality, but that is not generally the case for medical sensing or neurostimulation applications. The multi-mode devices provide a higher output power.

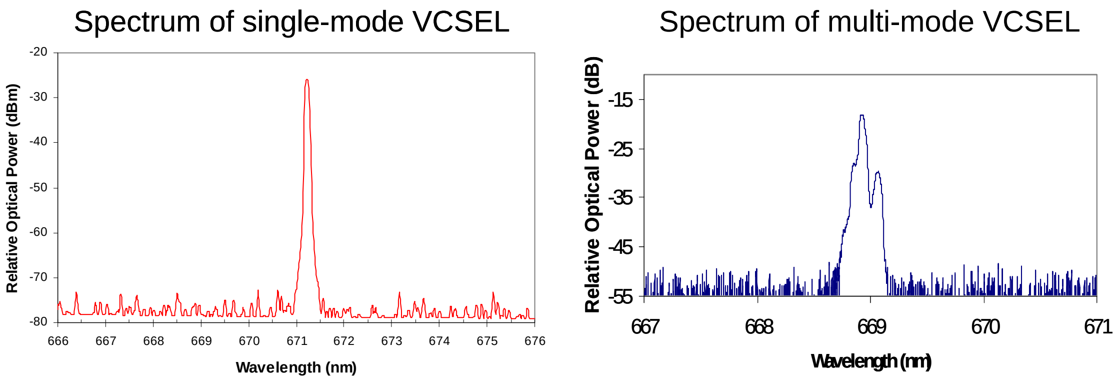


**Figure 3**. The spectral width of a single-mode and a multi-mode 670nm VCSEL. The linewidth of the single-mode device is limited by our measurement equipment. Even the linewidth of the multi-mode device is approximately 0.5nm, making both types of devices attractive for fluorescence based sensors.

One of the unique advantages of VCSELs is the ability to create arrays of lasers on a single chip with a very well-defined spacing. This can be done in one- or two-dimensional arrays and would allow one to create a scanning array for imaging, or for measuring an array of test sites. For neurostimulation the array allows one to stimulate multiple nerves simultaneously, or to choose a particular nerve without mechanical realignment. Figure 4 includes pictures of a segment of a 1x96 array of 670nm VCSELs on a 50µm pitch, and an 8x8 array on a 65µm pitch.

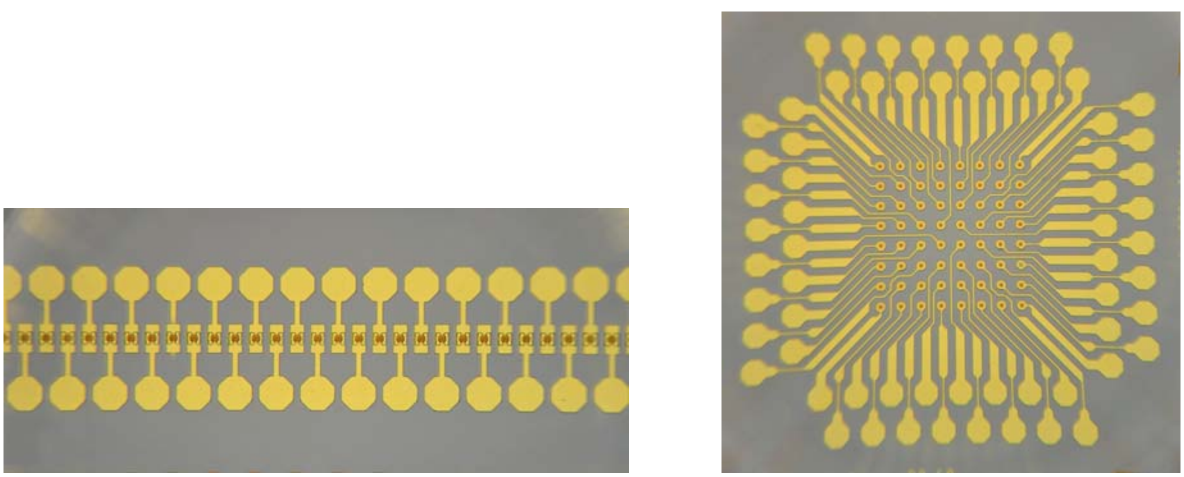

**Figure 4**. Photomicrographs of two 670nm VCSEL chips. The picture on the left is a segment of a 1x96 array of VCSELs on a 50µm pitch. The photo on the right is an 8x8 array on a 65µm pitch.

For such an array to be useful, a certain degree of uniformity in output power and required drive current and voltage is required. Figure 5 illustrates the uniformity that can be achieved. The plot on the left side shows the voltage and output power as a function of drive current for twelve 670nm single-mode VCSELs. The plot on the right shows the output power at 3 fixed currents for all 64 lasers in an 8x8 array.

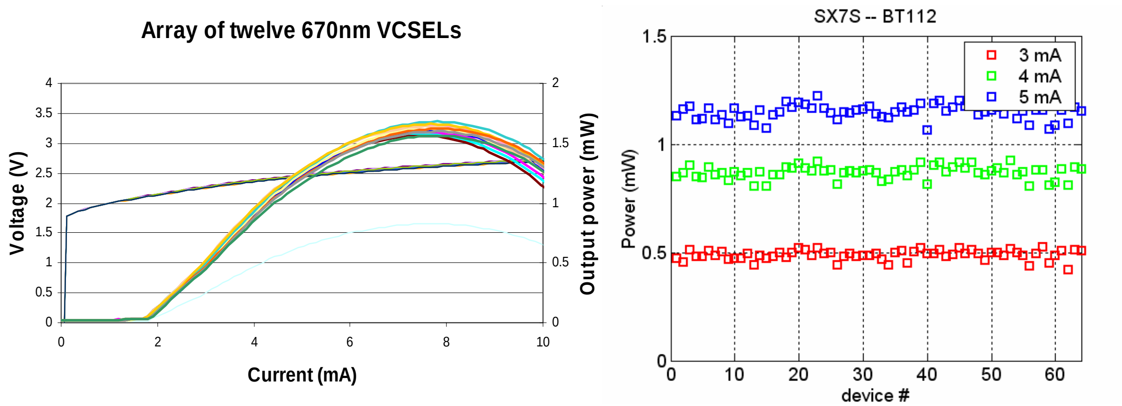


**Figure 5**. Illustration of the uniformity of 670nm VCSEL arrays. The plot on the left is the output power and voltage versus current for 12 devices in an array. The plot on the right illustrates the output power at three different fixed currents for all 64 lasers in an 8x8 arrays.

The vertically emitting nature of the VCSEL makes it compatible with the same range of packaging approaches as one can use for LEDs or many I.C. packages. Figure 6 demonstrates some of the packaging that we have already developed at Vixar for the VCSEL arrays. Three types of packages are shown. The round TO-header style package is frequently used for edge-emitting lasers, although EELs require a special pedestal to be included in the package so that the end of the chip is aimed out of the top of the package. This particular TO header is approximately 5mm in diameter, and has 5 pins, accommodating an array of up to 4 VCSELs. This style can easily be provided as a hermetic package. The plastic surface mount package is approximately 3mm on a side, and can accommodate up to 3 independently modulated lasers, either on a single chip, or separate chips. This is a suitable package for a multi-wavelength component, such as might be used by pulse oximetry. The third package is a ceramic surface mount package with a glass lid epoxied to the top, and accommodates our 8x8 array, allowing each laser to be individually modulated. The package could be hermetic with the appropriate technique for sealing the lid.

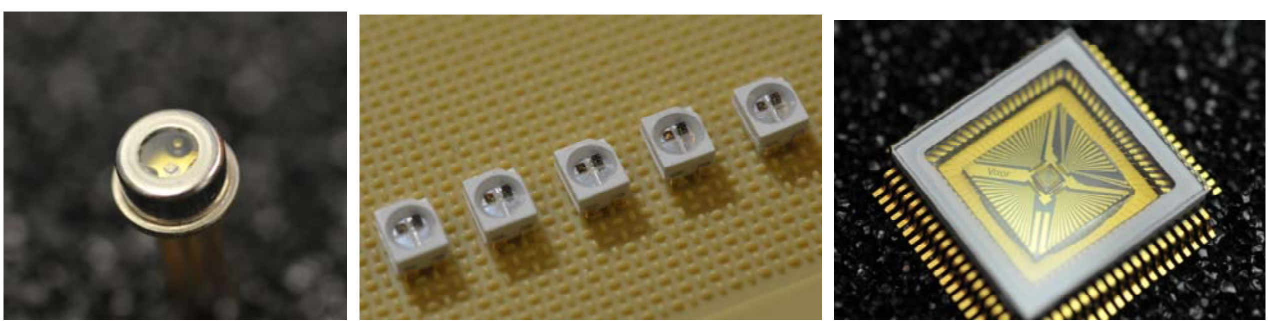

**Figure 6**. Three types of packages have been developed for the VCSELs. The package on the left is a TO header, approximately 5mm in diameter, and accommodates an array of up to 4 VCSELs which can be modulated indepdendently. The middle picture shows several plastic surface mount packages which can contain 1-3 chips, and is convenient for implementation of a multi-wavelength component. The package on the right is a ceramic surface mount package with a glass lid, and is designed for an 8x8 array.

One of the other interesting aspects of a VCSEL is that the vertically emitting nature allows integration with other components, and in some cases, that integration can be achieved at the wafer level. Vixar has done some research work on the wafer scale integration of lenses. Figure 7 is a picture of a portion of a wafer of VCSELs integrated with the lenses. After completion of the VCSEL wafer fabrication, stand-off posts are patterned using a thick (100µm) photoresist. Lenses are created on top of the stand-off posts by depositing drops of UV curable polymer using an ink-jet type process. The proper design resulted in a reduction of the beam divergence from approximately 10-12 degrees full-width $1/e^2$ to 2-4 degrees. A variety of post and VCSEL pitch and post diameter designs are visible in the picture. The smallest pitch visible is 75µm.

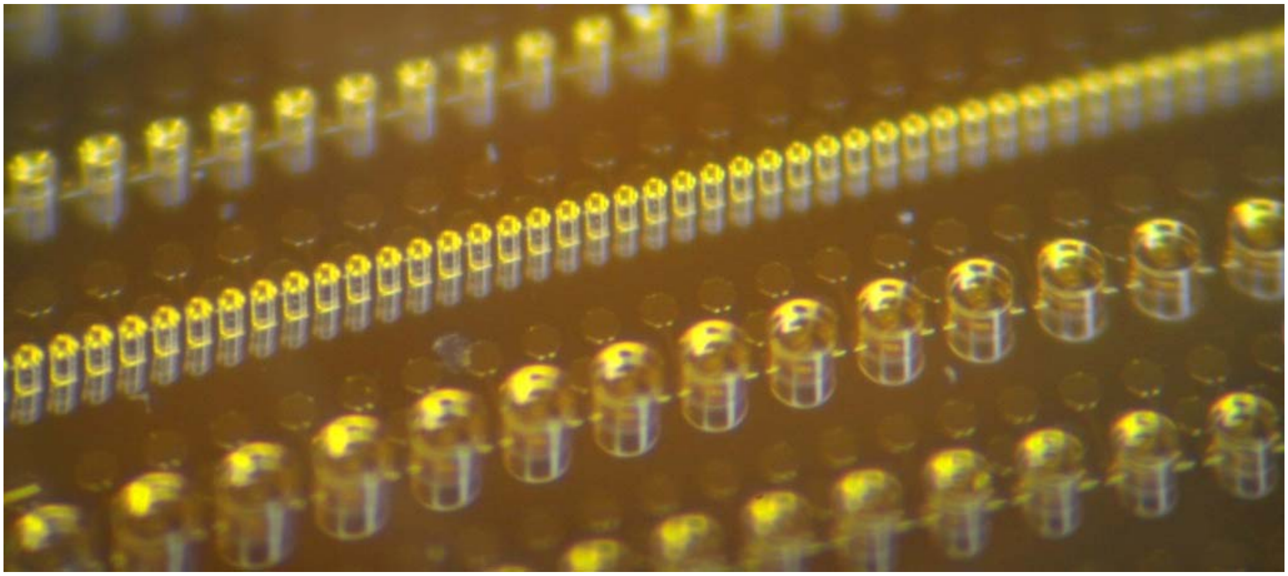

**Figure 7**. A photograph of one-dimensional arrays of VCSELs still on the wafer, integrated with standoff posts and lenses fabrication by drops of UV cured epoxy deposited with an inkjet like process. The posts are patterned in a thick photosensitive polymer. A pitch as small as 75µm has been achieved and is visible in the picture.

## 4. SUMMARY

The purpose of this paper has been to introduce the audience to a new tool in biomedical photonics, i.e. the Vertical Cavity Surface Emitting Laser, or VCSEL. While VCSELs emitting at 850nm have been available for some time, medical applications such as neurostimulation or non-invasive sensing require a range of different wavelengths that have not, to date, been readily available commercially. With the recent discovery of optical neurostimulation, VCSELs are a component that could enable miniaturized or implantable devices. The ability to create 1-D and 2-D arrays of closely spaced devices allows one to selectively stimulate a nerve without mechanical repositioning of the laser, and without stimulating its neighbors. Alternatively, an array could stimulate multiple sites simultaneously, as would be desirable in a cochlear implant, for instance. The ability to integrate the VCSEL into a chip scale module that includes driver and processing chips, or optical lensing, would also facilitate implantable devices.

In applications of optical sensing, the performance improvement of VCSELs compared to LEDs allows for more precisely chosen wavelengths that are less sensitive to temperature changes, faster devices so that frequency modulation can be used to reduce noise, arrays which can also reduce the need for mechanical alignment, and significantly lower power consumption, which enables wireless or implantable sensors.

VCSELs with wavelengths in the range from 670-980nm are now available, as well as devices at wavelengths > 1300nm. These developments can facilitate a wide range of biomedical applications.

## REFERENCES

[1] Soda, H., Iga, K., Kitahar, C., and Suematsu, Y., "GaInAsP/InP Surface Emitting Injection Lasers," Japanese Journal of Applied Physics **18** (12), 2329–2330, (1979).

[2] Koyama, F., Kinoshita, S., and Iga, K., "Room temperature continuous wave lasing characteristics of GaAs vertical cavity surface-emitting laser," Appl. Phys. Lett. **55**(3), 221-222, (1989)

[3] Jewell, J.L., McCall, S.L., Scherer, A., Houh, H.H., Whitaker, N.A., Gossard, A.C., and English, J.H., "Transverse modes, waveguide dispersion and 30-ps recovery in submicron GaAs/AlAs microresonators," Appl. Phys. Lett. **55,** 22-24 (1989)

[4] Geels, R., and Coldren, L.A., "Narrow-linewidth, low threshold vertical-cavity surface-emitting lasers," in 12th IEEE Int Semiconductor Laser Conf. **B-1**, 16-17 (1990).

[5] Wipiejewski, T., Panzlaf, K., Zeeb, E., Ebeling, K.J., "Submilliamp vertical cavity laser diode structure with 2.2nm continuous tuning," in 18th European Conf. Opt. Comm. '92, PDII-4 (1992)

[6] Lee, Y.H., Tell, B., Brown-Goebeler, K.F., Leibenguth, R.E., and Mattera, V.D., "Deep-red continuous wave top-surface-emitting vertical-cavity AlGaAs superlattice lasers," IEEE Photon Technol Lett **3**(2), 108-109 (1991)

[7] J.K. Guenter, R.A. Hawthorne, D.N.Granville, M.K. Hibbs-Brenner, and R.A.Moregan, "Reliability of proton-implanted VCSELs for data communications," Proc. SPIE **2683,** 1 (1996)
.
[8] "Chairman of Finisar ponders fiber's future," EE Times, ( 2006)

[9] M.H. Crawford, K.D. Choquette, R.J. Hickman, and K.M. Geib, "Performance of selectively oxidized AlGaInP –based visible VCSELs," OSA Trends Optics Photon Series **15,** 104-105 (1998)

[10] K. Johnson and M. Hibbs-Brenner, "High output power 670nm VCSELs," Proc SPIE **6484,** (2007)

[11] H.-E. Shin, Y.-G. Ju, H.-H. Shin, J.-H. Ser, T. Kim, E.-K. Lee, I. Kim, and Y.-H. Lee, "780nm oxidized vertical cavity surface-emitting lasers with $Al_{0.11}Ga_{0.89}As$ quantum wells," Electron Lett **32,** 1287-1288 (1996)

[12] M.C. Larson, M. Kondow, T. Kitatani, K. Nakahara, K. Tamura, H. Inoue and K. Uomi, "Room temperature pulsed operation of GaInNAs/GaAs long wavelength vertical cavity lasers," IEEE/LEOS '97, PD1.3 (1997)

[13] K.D. Choquette, J.F. Klem, A.J. Fischer, O. Blum, A.A. Allerman, I.J. Fritz, S.R. Kurtz, W.G. Breiland, R. Sieg, K.M. Geib, J.W. Scott, and R.L. Naone, "Room temperature continuous wave InGaAsN quantum wellvertical-cavity lasers emitting at 1.3 µm," Electron Lett **36,** 1388-1390 (2000)

[14] R. Shau, M. Ortsiefer, J. Rosskopf, G. Böhm, F. Köhler, and M.-C. Amann, "Vertical-cavity surface-emitting laser diodes at 1.55 µm with large output power and high operation temperature," Electron. Lett. **37**, 1295-1296 (2001)

[15] J.E. Sinex, "Pulse oximetry principals and limitations," J Emerg Med **17,** 59-67 (1999)

[16] S.J. Barker and J.J. Badal, "The measurement of dyshemoglibins and total hemoglobin by pulse oximetry," Curr Opin Anaesthesiol **21**, 805-810 (2008)

[17] C. Albano, L. Comandante, S. Nolan, "Innovations in the management of cerebral injury," Crit Care Nursing Q **28**, 135-149 (2005)

[18] D.E. Myers, L.D. Anderson, R.P. Seifert, J.P. Ortner, C.E. Cooper, G.J. Beilman, J.D. Mowlem, "Noninvasive method for measuring local hemoglobin oxygen saturation in tissue using wide-gap second derivative near-infrared spectroscopy," J Biomed Opt **10,** (2005)

[19] X. Cheng, J.M. Mao, X. Xu, M. Elmandjra, R. Bush, L. Christenson, B. O'Keefe, J. Bry, "Post-occlusive reactive hyperemia in patients with peripheral vascular disease," Clin Hemorheol Microcirc **31**, 11-21 (2004)

[20] M.P. Hudson, R.H. Christenson, K. Newby, A.L. Kaplan, E.M. Ohman, "Cardiac markers: point of care testing," Clin Chim Acta **284**, 223-237 (1999)

[21] A.H. Wu, A. Smith, R.H. Christenson, M.M. Murakami, F.S. Apple, "Evaluation of a point-of-care assay for cardiac markers for patients suspected of acute myocardial infarction," Clin Chim Acta **346**, 211-219 (2004)

[22] B.W. Lee, M.R. Olin, G.L. Johnson, R.J. Griffin, "In vitro and in vivo apoptosis detection using membrane permeant fluorescent-labeled inhibitors of caspases," Methods Mol Biol **414**, 109-135 (2008)

[23] Galvani, L., "De viribus electricitatis in motu musculari commentarius," De Bononiensi Scientiarum et Artium Instituto atque Academia Commentarii **7**, 363-418 (1791)

[24] Fritsch, G. and Hitzig, E., "," Arch Anat Physiol Wiss Med **37**, 300 (1870)

[25] Geddes, L.A. and Bourland, J.D., "," Med Biol Eng Comput **23**, 131 (1985)

[26] Counter, S., "Electromagnetic stimulation of the auditory system: Effects and side-effects," Scand Audiol Supp **37**, 1-32 (1993)

[27] Brummer, S. Robblee, L., Hambrecht, F., "Criteria for selecting electrodes for electrical stimulation: Theoretical and practical considerations," Ann NY Acad Sci **405**, 159-171 (1983)

[28] Shannon, R.A., "A model of safe levels for electrical stimulation," IEEE Trans Biomed Eng **39**, 424-426 (1992)

[29] Matsushima, J., Miyoshi, S., Takeichi, N., Uemi, N., Sakajiri, M., Ifukube, T., "A method to reduce the current spread in cochlear implants," Adv Otorhinolaryngol **52**, 106-109 (1997)

[30] Vanpoucke, F., Zarowski, A., Casselman, J., Frijns, J., Peeters, S., "The facial nerve canal: An important cochlear conduction path revealed by Clarion electrical field imaging," Otol Neurotol **25**, 282-289 (2004)

[31] Norton, S.I., "," Biomed Eng Online **2**, 6 (2003)

[32] Wagner, T., Gangitano, M., Romero, R., Theoret, H., Kobayashi, M., Anschel, D., Ives, J., Cuffin, N., Schomer, D., and Pascual-Leone, A., "," Neurosci Lett **354**, 91 (2004)

[33] Wells, J., Kao, C., Mariappan, K., Albea, J., Jansen, E.D., Konrad, P., and Mahadevan-Jansen, A., "," Optics Lett **30**, 504-506 (2005)

[34] Izzo, A.D., Richter, C.-P., Jansen, E.D., Walsh, J.T., "Laser Stimulation of the Auditory Nerve," Lasers in Surgery and Medicine **38**, 745-753 (2006)

[35] Izzo, A., Jansen, E.D., Bendett, M., Webb, J., Ralph, H. And Richter, C.P., "Optical parameter variability in laser nerve stimulation: a study of pulse duration, repetition rate, and wavelength," IEEE Trans Biomed Eng **54**, 1108-1114 (2007)

[36] Izzo, A.D., Walsh, J.T., Jansen, E.D., Bendett, M., Webb, J., Ralph, H., Richter, C.-P., "Optical Parameter Variability in Laser Nerve Stimulation: A Study of Pulse Duration, Repitition Rate, and Wavelength," IEEE Trans on Biomed Eng **54**, 1108-1114 (2007)

[37] Johnson, K., Hibbs-Brenner, M., "High Output Power Red VCSELs," Proceedings of the SPIE: Vertical Cavity Surface Emitting Lasers XI **6484**, (2007)