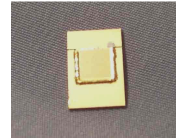
PRINCETON OPTRONICS



Vertical-Cavity Surface-Emitting Laser Technology

Vertical-Cavity Surface-Emitting Lasers (VCSELs) are a relatively recent type of semiconductor lasers. VCSELs were first invented in the mid-1980's. Very soon, VCSELs gained a reputation as a superior technology for short reach applications such as fiber-channel, Ethernet and intra-systems links. Then, within the first two years of commercial availability (1996), VCSELs became the technology of choice for local area networks, effectively displacing edge-emitter lasers. This success was mainly due to the VCSEL's lower manufacturing costs and higher reliability compared to edge-emitters.

The VCSEL structure

Semiconductor lasers consist of layers of semiconductor material grown on top of each other on a substrate (the "epi"). For VCSELs and edge-emitters, this growth is typically done in a molecular-beam-epitaxy (MBE) or metal-organic-chemical-vapor-deposition (MOCVD) growth reactor. The grown wafer is then processed accordingly to produce individual devices. Figure 1 summarizes the differences between VCSEL and edge-emitter processing.

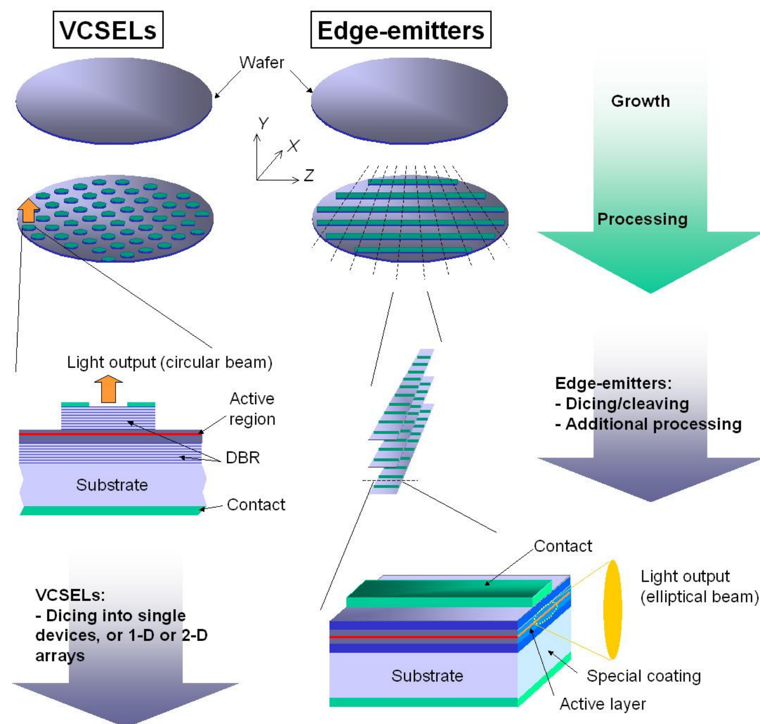


Figure 1 Comparison of the growth/processing flow of VCSEL and edge-emitter semiconductor lasers.

Princeton Optronics, Inc. * 1 Electronics Drive * Mercerville, New Jersey 08619
Voice: (609) 584-9696 * Fax: (609) 584-2448 * E-mail: sales@princetonoptronics.com * www.princetonoptronics.com

In a VCSEL, the active layer is sandwiched between two highly reflective mirrors (dubbed distributed Bragg reflectors, or DBRs) made up of several quarter-wavelength-thick layers of semiconductors of alternating high and low refractive index. The reflectivity of these mirrors is typically in the range 99.5~99.9%. As a result, the light oscillates *perpendicular* to the layers and escapes through the top (or bottom) of the device. Current and/or optical confinement is typically achieved through either selective-oxidation of an Aluminum-rich layer, ion-implantation, or even both for certain applications. The VCSELs can be designed for "top-emission" (at the epi/air interface) or "bottom-emission" (through the transparent substrate) in cases where "junction-down" soldering is required for more efficient heat-sinking for example. Figure 2 illustrates different common types of VCSEL structures.

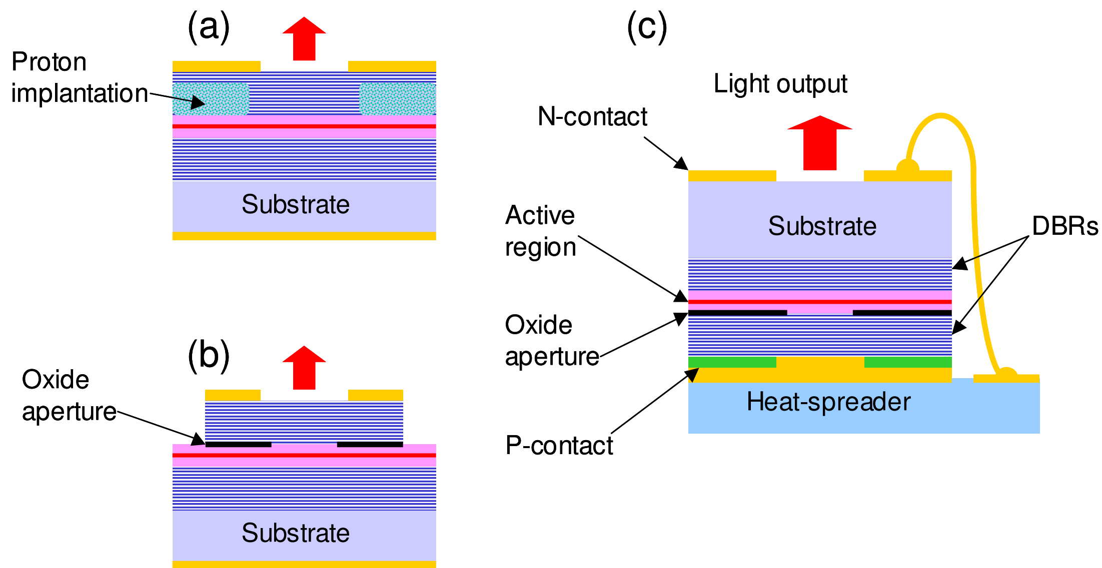


Figure 2 Three common types of VCSEL structures: (a) a top-emitting structure with proton implantation to confine the current, (b) a selectively-oxidized top-emitting structure to confine the optical modes and/or the current, and (c) a mounted bottom-emitting selectively-oxidized structure.

In contrast, edge-emitters are made up of cleaved bars diced from the wafers. Because of the high index of refraction contrast between air and the semiconductor material, the two cleaved facets act as mirrors. Hence, in the case of an edge-emitter, the light oscillates *parallel* to the layers and escapes side-ways. This simple structural difference between the VCSEL and the edge-emitter has important implications.

Since VCSELs are grown, processed and tested while still in the wafer form, there is significant economy of scale resulting from the ability to conduct parallel device processing, whereby equipment utilization and yields are maximized and set up times and labor content are minimized. In the case of a VCSEL (see Figure 1), the mirrors and active region are sequentially stacked along the Y axis during epitaxial growth. The VCSEL wafer then goes through etching and metalization steps to form the electrical contacts. At this point the wafer goes to test where individual laser devices are characterized on a pass-fail basis. Finally, the wafer is diced and the lasers are binned for

either higher-level assembly (typically >95%) or scrap (typically <5%). The following Figure shows a single high-power VCSEL device (>2W output power) packaged on a high-thermal conductivity submount.

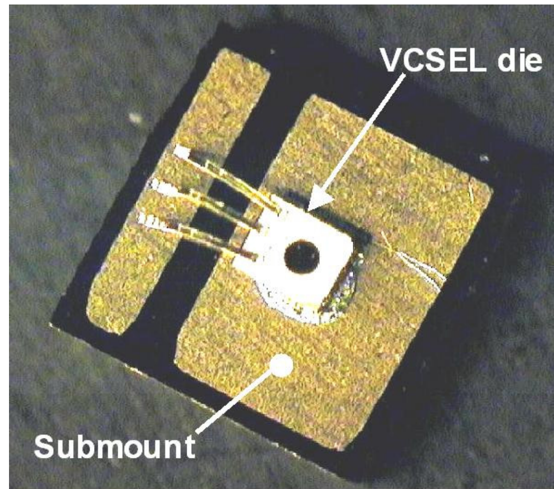


Figure 3 Packaged high-power VCSEL device (2W). The submount is 2mm x 2mm.

In a simple Fabry-Pérot edge-emitter the growth process also occurs along the Y axis, but only to create the active region as mirror coatings are later applied along the Z axis. After epitaxial growth, the wafer goes through the metalization step and is subsequently cleaved along the X axis, forming a series of wafer strips. The wafer strips are then stacked and mounted into a coating fixture. The Z axis edges of the wafer strips are then coated to form the device mirrors. This coating is a critical processing step for edge-emitters, as any coating imperfection will result in early and catastrophic failure of the devices due to catastrophical-optical-damage (COD). After this coating step, the wafer strips are diced to form discrete laser chips, which are then mounted onto carriers. Finally, the laser devices go into test.

It is also important to understand that VCSELs consume less material: in the case of a 3" wafer, a laser manufacturer can build about 15,000 VCSEL devices or approximately 4,000 edge-emitters of similar power levels.

In addition to these advantages, VCSEL also demonstrate excellent dynamic performances such as low threshold currents (a few micro-amps), low noise operation and high-speed digital modulation (10 Gb/s). Furthermore, although VCSELs have been confined to low-power applications – a few milli-Watts at most – they have the inherent potential of producing very high powers by processing large 2-D arrays. In contrast, edge-emitters cannot be processed in 2-D arrays.

VCSEL advantages

The many advantages offered by the VCSEL technology can be summarized in the following points:

1. **Wavelength stability:** The lasing wavelength in a VCSEL is very stable, since it is fixed by the short (1~1.5-wavelength thick) Fabry-Perot cavity. Contrary to edge-emitters, VCSELs can only operate in a single longitudinal mode.
2. **Wavelength uniformity & spectral width:** Growth technology has improved such that VCSEL 3" wafers are produced with less then a 2nm standard deviation for the cavity wavelength. This allows for the fabrication of VCSEL 2-D arrays with little wavelength variation between the elements of the array (<1nm full-width half-maximum spectral width). By contrast, edge-emitter bar-stacks suffer from significant wavelength variations from bar to bar since there is no intrinsic mechanism to stabilize the wavelength, resulting in a wide spectral width (3~5nm FWHM).
3. **Temperature sensitivity of wavelength:** The emission wavelength in VCSELs is ~5 times less sensitive to temperature variations than in edge-emitters. The reason is that in VCSELs, the lasing wavelength is defined by the optical thickness of the single-longitudinal-mode-cavity and that the temperature dependence of this optical thickness is minimal (the refractive index and physical thickness of the cavity have a weak dependence on temperature). On the other hand, the lasing wavelength in edge-emitters is defined by the peak-gain wavelength, which has a much stronger dependence on temperature. As a consequence, the spectral line-width for high-power arrays (where heating and temperature gradients can be significant) is much narrower in VCSEL arrays than in edge-emitter-arrays (bar-stacks). Also, over a 20°C change in temperature, the emission wavelength in a VCSEL will vary by less than 1.4nm (compared to ~7nm for edge-emitters).
4. **High Temperature Operation (chillerless operation for pumps):** Because VCSELs can operate reliably at temperatures up to 80 ^{o}C, they can be operated without refrigeration. Thus, the cooling system becomes very small, rugged and portable with this approach.
5. **Higher power per unit area:** Edge emitters deliver a maximum of about 500W/cm^2 because of the gap between bar to bar which has to be maintained for coolant flow, while VCSELs are delivering ~1200W/ cm^2 now and can deliver 2-4kW/ cm^2 in the near future.
6. **Beam Quality:** VCSELs emit a circular beam. Through proper cavity design VCSELs can also emit in a single transverse mode (circular Gaussian). This simple beam structure greatly reduces the complexity and cost of coupling/beam-shaping optics (compared to edge-emitters) and increases the coupling efficiency to the fiber or pumped medium. This has been a key selling point for the VCSEL technology in low-power markets.
7. **Reliability:** Because VCSELs are not subject to catastrophic optical damage (COD), their reliability is much higher than for edge-emitters. Typical FIT values (failures in one billion device-hours) for VCSELs are <10.
8. **Manufacturabilty and yield:** Manufacturability of VCSELs has been a key selling point for this technology. Because of complex manufacturing processes and reliability issue related to COD (catastrophic optical damage), edge-emitters have a low yield (edge-

emitter 980nm pump chip manufacturers typically only get ~500 chips out of a 2” wafer). On the other hand, yields for VCSELs exceed 90% (corresponds to ~5000 high-power chips from a 2” wafer). In fact, because of its planar attributes, VCSEL manufacturing is identical to standard IC Silicon processing.

9. **Scalability:** For high-power applications, a key advantage of VCSELs is that they can be directly processed into monolithic 2-D arrays, whereas this is not possible for edge-emitters (only 1-D monolithic arrays are possible). In addition, a complex and thermally inefficient mounting scheme is required to mount edge-emitter bars in stacks.

10. **Packaging and heat-sinking:** Mounting of large high-power VCSEL 2-D arrays in a “junction-down” configuration is straightforward (similar to micro-processor packaging), making the heat-removal process very efficient, as the heat has to traverse only a few microns of AlGaAs material. Record thermal impedances of <0.16K/W have been demonstrated for 5mm x 5mm 2-D VCSEL arrays.

11. **Cost:** With the simple processing and heat-sinking technology it becomes much easier to package 2-D VCSEL arrays than an equivalent edge-emitter bar-stack. The established existing silicon industry heat-sinking technology can be used for heat removal for very high power arrays. This will significantly reduce the cost of the high-power module. Currently, cost of the laser bars is the dominant cost for the DPSS lasers.