Wafer-fused VCSELs shape up for enterprise applications

Swiss start-up BeamExpress has developed a high-volume manufacturing process for long-wavelength singlemode VCSELs that combines the strengths of InP and GaAs technology. Company founder and chief scientist **Eli Kapon** outlines the wafer-fusion technique.

Vertical cavity surface-emitting lasers (VCSELs) offer numerous advantages over their edge-emitting counterparts for various different optoelectronics applications owing to their optical cavity configuration. In particular, VCSELs exhibit lower electrical power consumption, pure single-wavelength operation, easier coupling into singlemode optical fibers, compatibility with other optical elements for simpler packaging, and lower manufacturing costs thanks to the possibility of on-wafer testing.

In fact, short-wavelength (<1 µm) VCSELs dominate very-short-haul (<100 m) data-communication and optical-interconnect markets and are also increasingly being employed in sensor applications. This success results from a relatively simple fabrication technology, which relies on GaAs-based epitaxial wafers incorporating AlGaAs distributed Bragg reflectors (DBRs) and an (In)GaAs/AlGaAs quantum well (QW) active region.

Playing catch-up

VCSELs operating at longer wavelengths, particularly the 1310 and 1550 nm telecommunication wavebands, are attractive solutions for developing low-cost, wavelength-controlled sources in local-area and metropolitan optical fiber networks spanning transmission distances of between 100 m and 100 km. The development of these long-wavelength emitters, however, has lagged behind their shorter-wavelength counterparts. For best performance, these devices require GaAs/AlGaAs DBRs that offer a large refractive index contrast between their layers and a high thermal conductivity coefficient, and InP-based QW active regions with a high optical gain at up to 100 °C.

Using such a combination of III-V semiconductor materials is particularly important when tackling the challenge of developing singlemode VCSELs that emit at least 1–2 mW at temperatures of 70–90 °C. This performance is essential to ensure reliable operation of enterprise data and telecom networks, which represent the largest application sector for long-wavelength VCSELs.

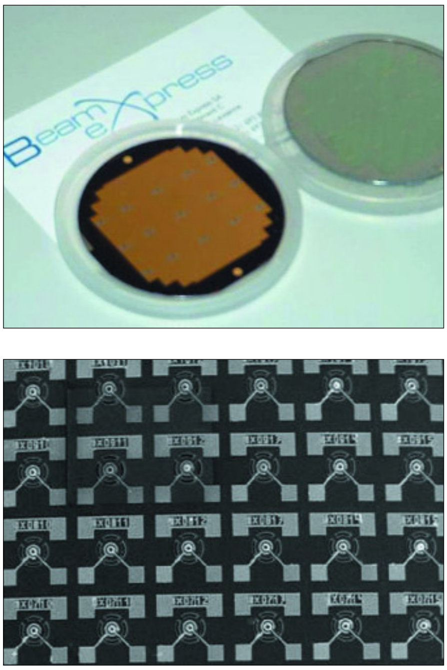

Fig. 1. BeamExpress's 2 inch locally fused wafers (top) combine GaAs-based DBRs and InP-based active regions. A micrograph (above) shows several VCSEL devices fabricated on a hybrid wafer.

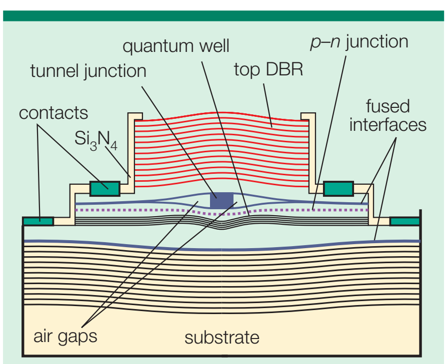

Fig. 2. A cross-section of BeamExpress's long-wavelength VCSEL, containing an InP-based active region with several strained InAlGaAs quantum wells and a heavily doped *p–n* tunnel junction sandwiched between two GaAs-based DBRs.

The difficulties associated with mixing GaAs- and InP-based structures using conventional epitaxy has prompted exploration of alternative techniques for making such devices. Approaches include using highly strained QWs or quantum dot GaAs/InGaAs active regions; dilute-nitride GaInNAs/GaAs active regions; InP-based metamorphic DBRs; dielectric mirrors with InP-based active regions; and antimonide compounds. Although these techniques have made considerable progress, they still suffer limitations in terms of the choice of emission wavelengths and/or their singlemode output power.

A symbiotic relationship

An attractive alternative to single-substrate VCSEL technologies is wafer fusion, where the device is constructed by bonding together the separate components of the VCSEL cavity that are grown on their host substrates. This approach combines InP-based active regions with GaAs-based DBRs to give the best VCSEL performance.

A modified wafer-fusion technique, called localized wafer fusion, has been developed at the Laboratory of Physics of Nanostructures in the Swiss Federal Institute of Technology in Lausanne and is now being exploited by local start-up BeamExpress. In this technique, one or more wafer surfaces are structured using conventional lithography prior to the fusion step. This surface structuring defines the optical cavity and the carrier-confinement region inside the VCSEL. In particular, it permits precise adjustment of the laser's optical-cavity length, which in turn enables nanometer-scale precision when setting its emission wavelength. In addition, localized fusion helps to regulate the fusion process across the rest of the wafer, yielding reproducible high-quality fused interfaces.

BeamExpress has recently fabricated 2 inch double-fused VCSEL wafers with high uniformity and excellent repeatability, thereby establishing localized wafer fusion as a viable mass-production technology (figure 1). Such wafers employ an industry-standard small die size, enabling production of a large number of devices per wafer.

Figure 2 shows a localized, double-wafer-fused VCSEL. The active region typically incorporates several InAlGaAs strained QWs and a heavily doped *p–n* tunnel junction, grown on an InP substrate by MOCVD using silicon and carbon dopants. Lateral electrical and optical confinement is obtained by etching mesas through the tunnel junction. The top and bottom DBRs, typically containing 21.5 and 35 periods of undoped $Al_{0.9}Ga_{0.1}As$/GaAs quarter-wavelength layers grown on GaAs substrates, respectively, are fused to either side of the active cavity material.

Mesas at the fused interface are surrounded by lens-shaped nanogaps formed by plastic deformation of the fused wafers. Current is driven through the tunnel junction into the active region via *n*-type intracavity layers. A reverse-biased *p–n* junction around the mesa provides efficient lateral-current confinement.

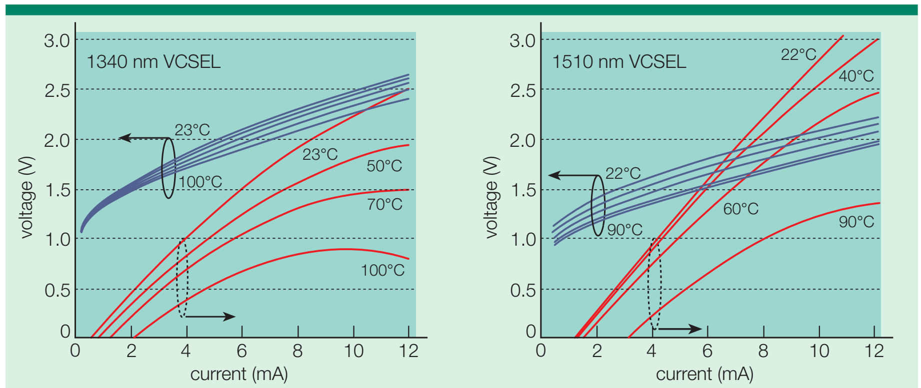

Fig. 3. The performance of BeamExpress's VCSELs at high-temperatures establishes the devices' credentials for deployment in enterprise data and telecom networks.

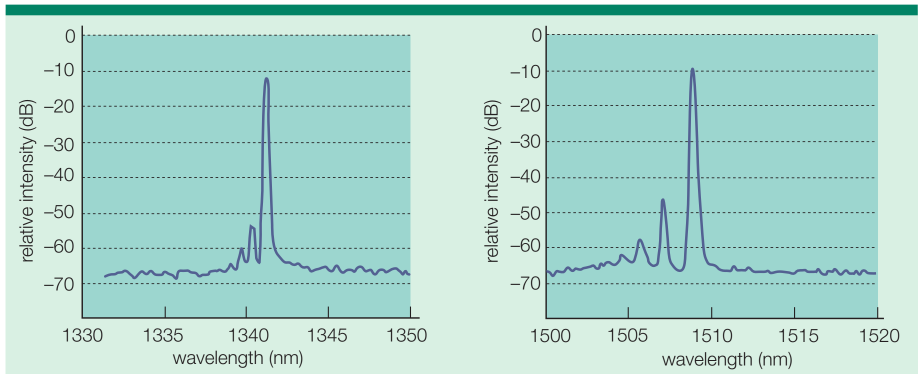

Fig. 4. With a sidemode suppression ratio of at least 35 dB and output powers of more than 1 mW, BeamExpress's VCSELs are potential candidates for use in 10 Gigabit Ethernet.

Optimized operation

The light-current-voltage characteristics at different ambient temperatures for 1310 and 1550 nm-emitting devices are shown in figure 3. Optimizing the device design leads to threshold currents of less than 3 mA and a diode voltage of less than 2.5 V throughout the temperature range for both wavebands. At 85 °C, singlemode optical powers of 1.2 mW at 1340 nm and 1.6 mW at 1510 nm have been obtained, and a sidemode suppression ratio of better than 35 dB was achieved at all of the tested temperatures (figure 4).

Operation at selected wavelengths conforming to the standardized course wavelength-division multiplexing (CWDM) grid has been demonstrated with a mesa-trimming technique that involves setting the cavity length prior to the fusion step. Of equal importance, the high singlemode power of BeamExpress's localized wafer-fused VCSELs is obtained without compromising either beam shape or direct modulation speed.

By employing 7 µm diameter apertures, circularly symmetric fundamental-mode beams with full width at half maximum values in the region of 7.5 and 9.5° are obtained for 1310 and 1550 nm VCSELs, respectively. These beam shapes have a high coupling efficiency into singlemode fibers (80 and 70% with a lens for 1300 and 1550 nm wavelengths, respectively, and 50% for butt-coupling at both wavelengths). Direct modulation at 3.125 Gbit/s is achieved with devices at both wavebands, and the extension of modulation speeds to 10 Gbit/s is under development.

BeamExpress's devices exhibit singlemode output powers at 85 °C that are two to three times as high as those of other 1310 and 1550 nm-emitting VCSELs. Due to the significantly improved coupling efficiency into singlemode optical fibers, these VCSELs can now effectively replace edge-emitting distributed feedback (DFB) lasers operating at much higher (>5 mW) singlemode powers. When operating at high temperatures (70–90 °C), the electrical power consumption of a BeamExpress VCSEL is one-tenth that of a comparable DFB edge-emitting laser.

This very low power consumption enables VCSELs to be packaged in far more compact modules, opening the way to new generations of low-cost, high-performance optical transceivers. Low power consumption is just one aspect of the ease of integration of these devices, which will play a major role in shrinking the footprint and the cost of VCSEL-based optical modules.

One example is 10G-BASE-LX4 transceivers, the four-wavelength CWDM standard for 10 Gigabit Ethernet. Here, BeamExpress's VCSEL technology offers a substantial cost advantage in multiplexing the multiwavelength laser array, making it suitable for high-volume low-cost manufacturing. In addition, efficient VCSELs operating in the 1310 and 1550 nm telecommunication wavebands enable production of 8-channel CWDM VCSEL arrays, with yet more channels available if water-free fibers are introduced.

BeamExpress is now working with manufacturing partners to optimize future high-volume production of localized wafer-fused long-wavelength VCSELs. A fully automated wafer-fusion process allied to subsequent processing steps that resemble those established for short-wavelength VCSEL manufacturing indicates that competitive chip costs will be possible with this technology. The company is engaged in intensive reliability tests for all aspects of the technology, and encouraging results have already been obtained. Long-wavelength VCSEL prototypes are also being sampled by selected customers.