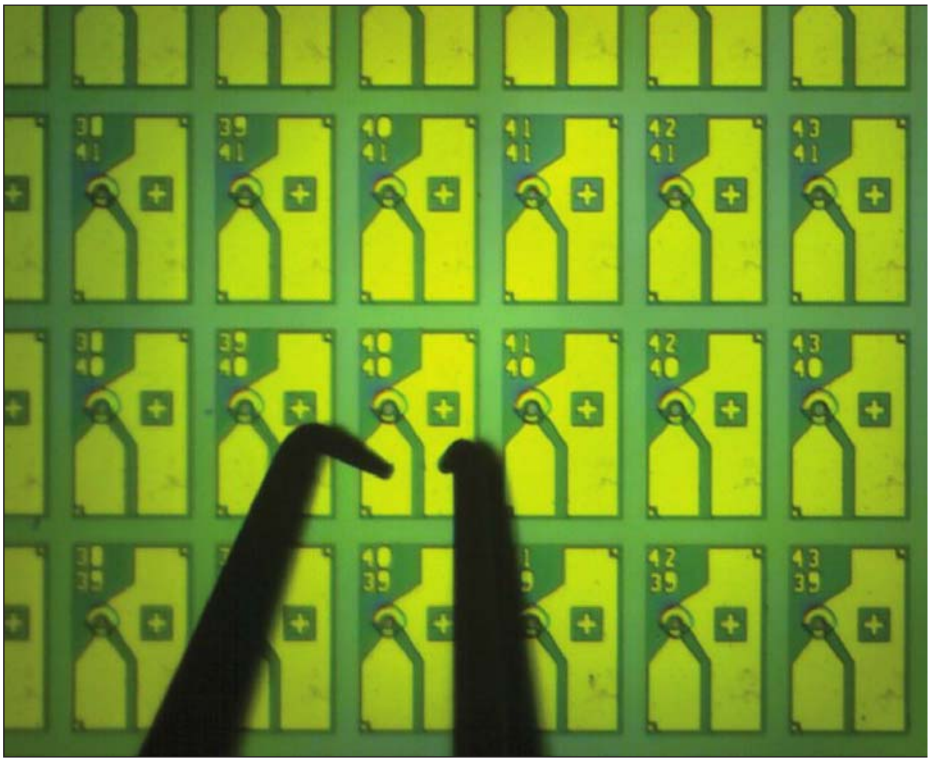

Ultra-low power VCSELs for **optical networks**

It is essential that tomorrow's optical networks are built with far more efficient components to prevent the continual ramp in internet traffic from significantly increasing global energy consumption. One promising device that will help in this endeavour is a 1310 nm VCSEL formed by fusing together active regions grown on InP wafers and mirrors formed on GaAs substrates, says **Alexei Sirbu from Ecole Polytechnique Fédérale de Lausanne (EPFL) and Eli Kapon from EPFL and BeamExpress.**

SURGING SMARTPHONE SALES and a growth in internet TV are helping to drive a rapid rise in Internet traffic. This is placing increasing strain on infrastructure, including optical networks and data centres. Upgrading capacity is essential, but this must go hand-in-hand with the introduction of more efficient components that do not prevent a hike in electricity consumption, which is already substantial. This can be partly addressed by turning to new classes of semiconductor devices that deliver tremendous improvements in efficiency.

One opportunity to do just that is to switch from the incumbent 1310 nm laser source – a directly modulated, uncooled distributed-feedback (DFB) laser – to a novel, wafer-fused VCSEL. DFB lasers are widely used to form part of 10 Gbit/s transceivers that have a reach of 10 km and are currently being shipped in high volumes and deployed in Ethernet and local area networks.

To cope with the rising levels of traffic, these transceivers are just starting to be replaced with 40 Gbit/s transmit-receive engines that comply to the IEEE Standard 802.3ba, which was ratified in June 2010. These engines, which will totally substitute 10 Gbit/s transceivers by the end of this decade, employ coarse-wavelength-division multiplexing (CWDM) technology and feature four uncooled 10 Gbit/s DFB lasers emitting at 1271 nm , 1291 nm, 1311 nm and 1331 nm. Using this laser source, transceivers have a typical power consumption of 3.5 W, with a significant proportion drawn by the laser drivers.

Power consumption could be slashed by replacing these DFB lasers with VCSELs. The power consumption of a transceiver in a Quad Small Form-factor Pluggable (QSFP) multi-source agreement (MSA) package, comprising a 4x10 Gbit/s VCSEL transmission optical sub-assembly (TOSA), is as low as 1 W – that is less than that of a single 10GBASE-LR transceiver based on DFB lasers, which has a typical power consumption of 1.2 W. So, in short, VCSELs offer a unique possibility to replace existing 10 Gbit/s transceivers with 40 Gbit/s transceivers without increasing the total power consumption of existing equipment.

Switching from DFB lasers to VCSELs can also drive down production costs. On-wafer testing is possible with VCSELs, but not with DFB lasers, which require a testing process that makes a significant contribution to overall production costs.

Above: VCSELs offer on-wafer testing, which can trim manufacturing costs compared to edge-emitting lasers

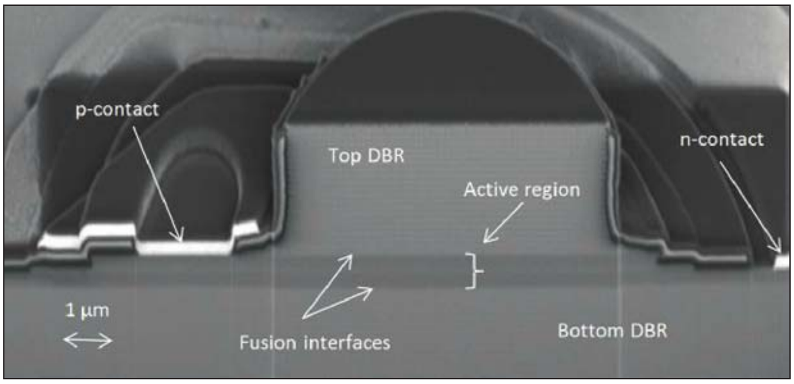

Figure 1. Similar to datacom VCSELs, wafer-fused 1310 nm VCSELs employ a GaAs substrate and can be fabricated in large volumes using standard processing steps in foundries that normally process AlGaAs/Ga(In)As-based devices

A further advantage of the VCSEL over its incumbent cousin is its substantially reduced sensitivity to changes in temperature. It is possible to design a VCSEL in a way that ensures that its threshold current does not change with temperature, but for DFBs, the threshold current at elevated temperature is always several times larger than that at room temperature. With currently developed VCSELs, 10 Gbit/s operation is achievable at a constant bias current of typically 7 mA across the full temperature range from 0°C to 85 °C, but with standard DFBs, the bias current must be constantly adjusted, depending on the ambient temperature. The operation of 10 Gbit/s VCSELs at a bias current at or below 7 mA enables the use of very low-power-consumption VCSEL driver arrays, which were developed for short-wavelength datacom VCSELs – these emit at 1μm or less.

Wafer fusion

Several approaches can be taken to fabricate 1310 nm VCSELs, including that pioneered by our team from Ecole Polytechnique Fédérale de Lausanne and BeamExpress. Our approach, which we have been developing for several years, has advanced to the stage where it is mature enough to challenge existing un-cooled 10 Gbit/s DFB lasers used for communication applications.

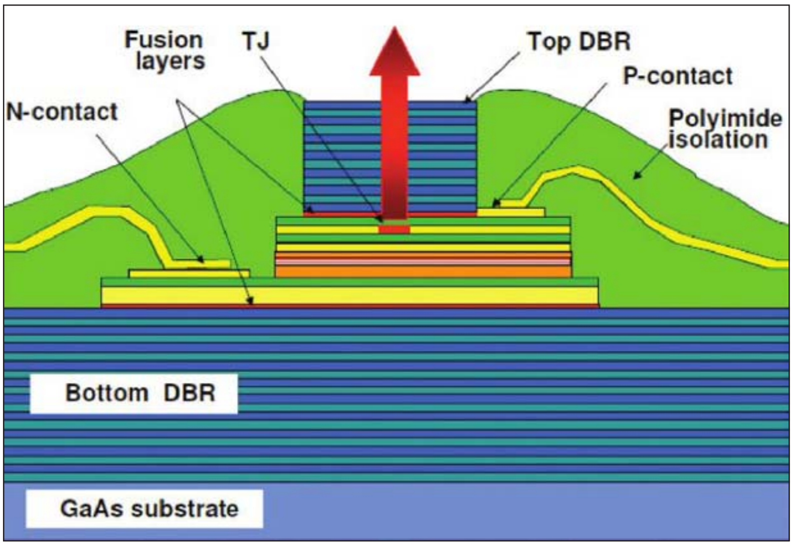

Figure 2. Wafer-fused VCSELs employ the same InP-based active region material system as well-established DFB lasers and the same AlGaAs/GaAs distributed Bragg reflectors as short-wavelength datacom VCSELs. In these devices, carrier injection into the active region is performed by a tunnel junction. Compared with standard datacom VCSELs, this new element allows implementation of un-doped DBRs that result in considerable reduction of optical losses in the VCSEL cavity

Wafer-fused VCSELs are essentially a marriage of an InP-based active region that is used in well-established DFB lasers and the AlGaAs/GaAs distributed Bragg reflectors that are employed in short-wavelength datacom VCSELs (see Figures 1 and 2). In these hybrids, a tunnel junction provides carrier injection into the active region. Compared with a standard datacom VCSEL, this new element allows implementation of un-doped DBRs that deliver a considerable reduction in optical losses in the VCSEL cavity. This enhancement counters the reduction in material gain resulting from the switch from a GaAs-based active region to one revolving around InAlGaAs/InP, and ultimately allows the 1310 nm band VCSEL to deliver a performance that is comparable to its shorter-wavelength sibling used in datacom and optical interconnects.

Our wafer-fused VCSELs share other similarities with their datacomm cousins: They are formed on a GaAs substrate, and they can be fabricated in large volumes in foundries using standard processing steps that are normally employed for producing AlGaAs/Ga(In)As-based devices. Device fabrication begins by taking two, 2-inch wafers with AlGaAs/GaAs DBRs and fusing them to either side of an InP-based active cavity with standard wafer-bonding equipment.

Despite using elevated temperature of 600°C, and the substantial difference in thermal expansion coefficients of GaAs-based and InP-based wafers that have been grown by MOCVD, our fused wafers have a very low density of defects in the active region (see Figure 3). This great material quality, and an active region that is incredibly small – its typical diameter is only 7 μm – leads to devices that are nearly always defect free, and are produced with a very high fabrication yield.

A great strength of the wafer fusion technique is that it allows the precise wavelength of the VCSEL to be set. This is crucial for making products that are based on CWDM, because this application demands laser emission within ±2 nm of the target wavelength. Fulfilling this requirement is possible with our VCSEL design, because devices are assembled from three separately grown elements: one active region and two DBRs. As a result, before the first and second fusion steps are undertaken, the active cavity and the DBRs can be adjusted by a proper selection and/or selective chemical etching.

In sharp contrast, in VCSELs with dielectric DBRs, the mode is tightly confined in the active region and cavity adjustments require selective etching of the InP-based material – this reduces the precision of wavelength setting. There are also 1310 nm VCSELs that are formed by growing a semiconductor active region and DBRs in a single run, and with type of design it is again very challenging to hit the wavelength specifications. Standard epitaxial growth techniques have a thickness tolerance of about 1 percent, and this leads to variations in emission wavelength that exceed the tolerance that is acceptable for components based on CDWM.

After the VCSEL wafers have been formed, they are processed with standard steps, such as dry and wet chemical etching, and deposition of dielectrics and metals for contacts and bond-pads. This creates about 15,000 VCSELs on a wafer, which are all characterised at room and elevated temperatures using automated probe stations. Only after performing all the necessary tests, including high-speed modulation characterization on selected devices, are dies scribed from the VCSEL wafer.

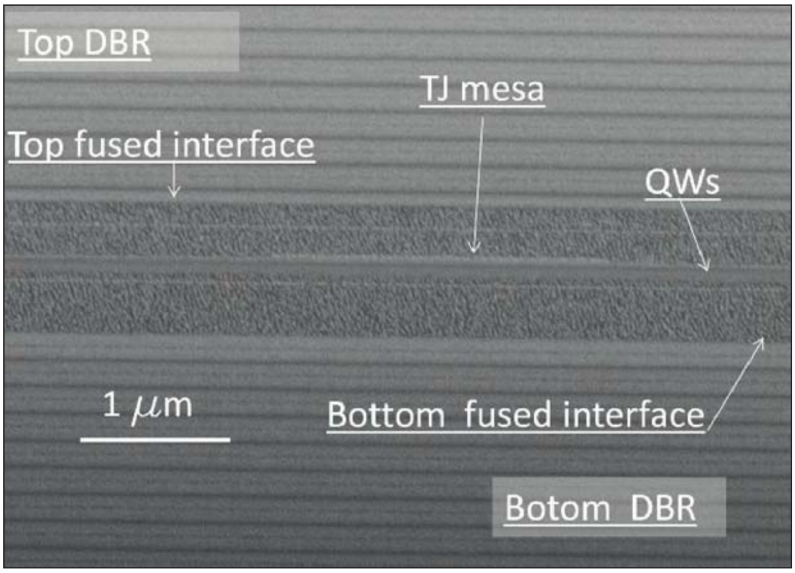

Figure 3. Even though the wafer fusion process is performed at an elevated temperature of 600°C and the significant thermal expansion coefficient mismatch between GaAs-based and InP wafers, the current fabrication process allows production of fused wafers with a defect-free, InP-based active region of the VCSEL

Coping with the heat

These VCSELs can deliver 10 Gbit/s error-free transmission over 10 km of standard, single-mode fibre at ambient temperatures as high as 100°C (see Figures 4 and 5). These tests were performed without any cooling at a constant bias current of 8 mA, demonstrating that these wafer-fused VCSELs can perform excellently in the category of un-cooled 1310 nm communication lasers.

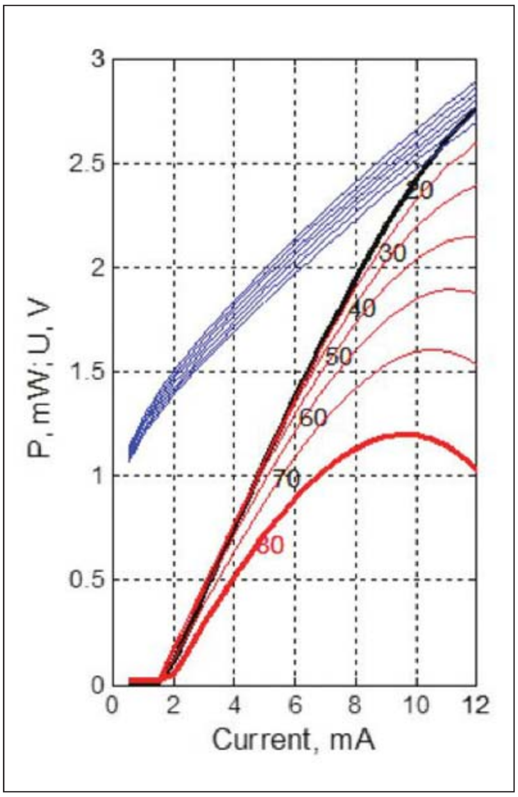

Figure 4. VCSELs can be designed in a way that the threshold current does not change with temperature, while for DFBs the threshold current at elevated temperature is several times larger than that at room temperature

If these lasers are to be deployed in industry, their excellent performance must be combined with a level of reliability that conforms to industry standards. To determine if that is the case, we subjected these devices to a two-year reliability test programme: They passed all the assessments associated with the GR-468-CORE Telcordia Generic Reliability Assurance Requirements for Optoelectronic Devices. These assessments, including different mechanical tests like shocks, vibrations and die shear; temperature cycling and electrical tests; have shown that wafer-fused VCSELs behave in the same way as existing, commercially available lasers.

This set of tests included accelerated life tests on first-generation devices operating at 10 Gbit/s at a 9 mA driving current. The results of this assessment enabled us to predict that, at 25°C and 70°C ambient temperatures, times to 1 percent failure are 291 years and 19 years, respectively (see Figure 6).

We have searched for defects in the active region of our device with various imaging techniques. This includes the use of scanning and transmission electron microscopy to scrutinise cross-sections and lamellas from degraded VCSEL material, which has been prepared for inspection via focused-ion-beam milling. The failure analysis study is ongoing and, if necessary, further optimization of fabrication will be implemented in new generations of the devices.

> “Results show that our wafer-fused VCSELs are ready for entering the rapidly growing market of 40GBASE-LR4 transceivers for data centres and telecom local area networks. It is clear to us that the telecom industry is set to benefit from the unique opportunity offered by this new generation of un-cooled 10 Gbit/s 1310 nm communication lasers”

Results on more recent devices are even more promising. For VCSELs operating at 10 Gbit/s at a bias current of 7 mA, the predicted time to 1 percent failure at 70°C is now 50 years. Thanks to this progress, our wafer-fused VCSELs largely meet the telecom industry requirements for the time to 1 percent failure, which is more than 10 years at 70°C (see Figure 7).

These results show that our wafer-fused VCSELs are ready for entering the rapidly growing market of 40GBASE-LR4 transceivers for data centres and telecom local area networks. It is clear to us that the telecom industry is set to benefit from the unique opportunity offered by this new generation of un-cooled 10 Gbit/s 1310 nm communication lasers, which can reduce the cost and the power consumption of 40 Gbit/s modules to the level of 10 Gbit/s modules existing today.

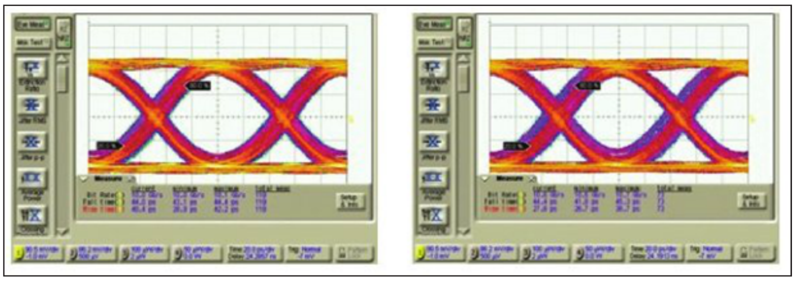

Figure 5. While with currently developed VCSELs, 10 Gbit/s operation can be achieved at a constant bias current of typically 7 mA in the full temperature range from 0°C to 85 °C, with standard DFBs the bias current needs to be constantly adjusted depending on the ambient temperature (eye diagrams above for 20°C). 10 Gbit/s operation at a bias current at or below 7 mA allows the application of very low power consumption VCSEL driver arrays that were developed for short wavelength (<1μm) datacom VCSELs

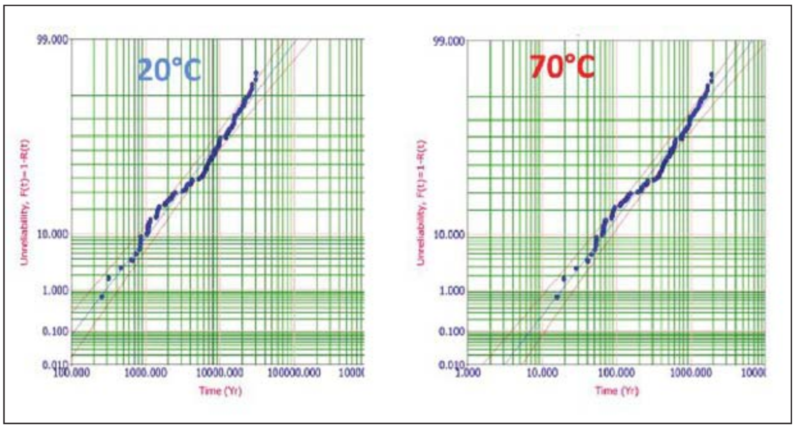

Figure 6. Using the aging parameters of the first generation devices that can be modulated at 10 Gbit/s at 9 mA bias current, one can predict time to 1 percent failure of 291 years and 19 years at 25°C and 70°C ambient temperatures, respectively

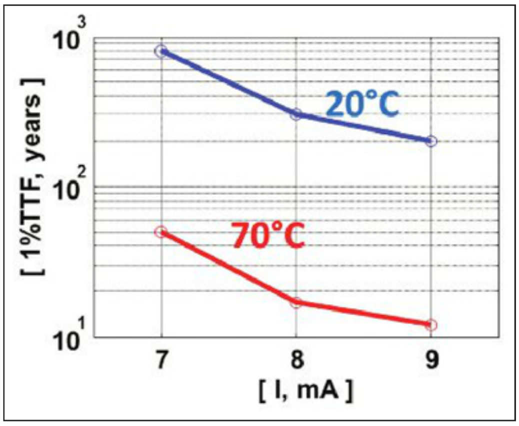

Figure 7. On recent devices that operate at 10 Gbit/s at a bias currents of 7 mA, the predicted time to 1 percent failure at 70°C increases to 50 years

One of the most promising opportunities for these 40GBASE-LR4 1W transceivers is as replacements for the 1 W QSFP packages, which are standard modules normally employed in the switching racks of data centres. If this upgrade is made, it is a very efficient way to considerably increase the throughput of existing data centres.

Although, like with any new technology, there are always concerns associated with the adoption of any new class of device, those that make the leap promise to slash the power consumption of their transceivers, and help to reduce the escalating energy costs associated with internet traffic.