Short- and long-reach of new VCSEL applications

Vertical-cavity surface emitting laser (VCSEL) technology has established itself in the short-range optical data link and optical mouse markets. New applications such as very-short-range data and bio-analysis beckon. Mike Cooke reports.

Much of the recent development in VCSEL technology has been driven by short- and very-short-range optical data link opportunities (Table 1). Companies such as Google, Intel, HP and IBM have been among the leaders in developing optical data interconnects, and it seems likely that intra-rack systems will be standard within a year. In a few years, chip-mounted VCSEL arrays could be used for high-speed data communications at even closer quarters.

In terms of performance, VCSELs can deliver a near-circular output beam with a small full-divergence angle and a fundamental mode with near-Gaussian intensity profile. The smaller divergence angle compared with other technologies allows for better coupling efficiency with optical fiber.

VCSELs also have low threshold current and power consumption, along with high output power and high slope efficiency. The low threshold enables direct modulation of these devices at high frequency. Further desirable features include thermal stability at milliwatts of peak output power.

The production advantages of the VCSEL format include simplified packaging and small size compared with edge-emitting lasers. The devices are produced in a planar process that allows testing and characterization at an earlier stage in the production process, even on-wafer, giving tighter production control at low cost. These features enable high-reliability products and packaging versatility.

Further, low-cost parallel devices are possible with the VCSELs produced in 2D-arrays. Among the attractive applications of VCSEL arrays is optical interconnects for future high-performance computer architectures.

Researchers are seeking to build on these characteristics and find ways to increase the modulation bandwidth while simultaneously improving device reliability, power efficiency, modal and spectral characteristics, thermal management, and so on.

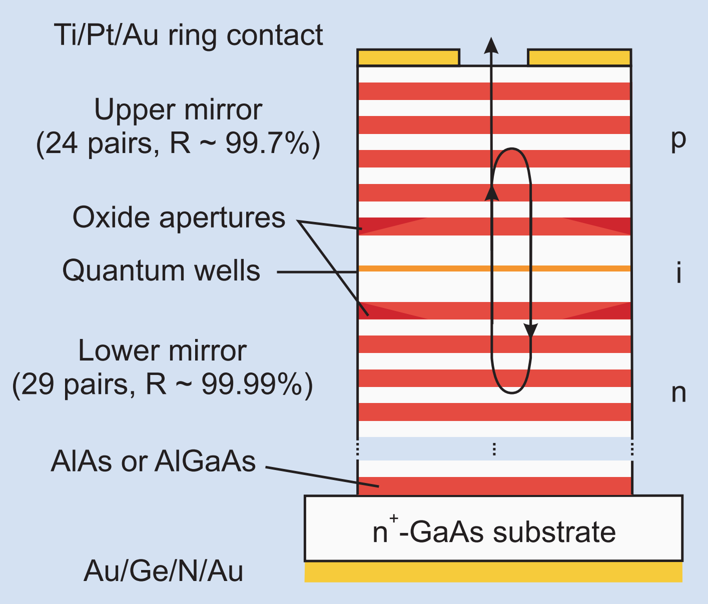

Figure 1. Schematic of distributed Bragg mirrors and quantum well structures found in typical 850nm oxide-confined VCSEL.

Table 1. Some recent achievements in VCSEL modulation at various wavelengths.

Wavelength	Distance	Room temp.	High temp.	Demonstration parameters
850nm	up to 300m	40Gb/s	25Gb/s @ 85°C	40Gb/s @ RT with ~3m fiber, 35Gb/s @ RT, 25Gb/s @ 85°C with 100m fiber
980nm	several meters	35Gb/s	25Gb/s @ 85°C	35Gb/s @ RT with ~1 m, 25Gb/s @ 85°C with ~3m fiber
1100nm	several meters	40Gb/s	25Gb/s @100°C	both with ~3m of fiber
1300nm	~100km	10Gb/s		
1550nm	~100km	35Gb/s	25Gb/s @ 55°C	

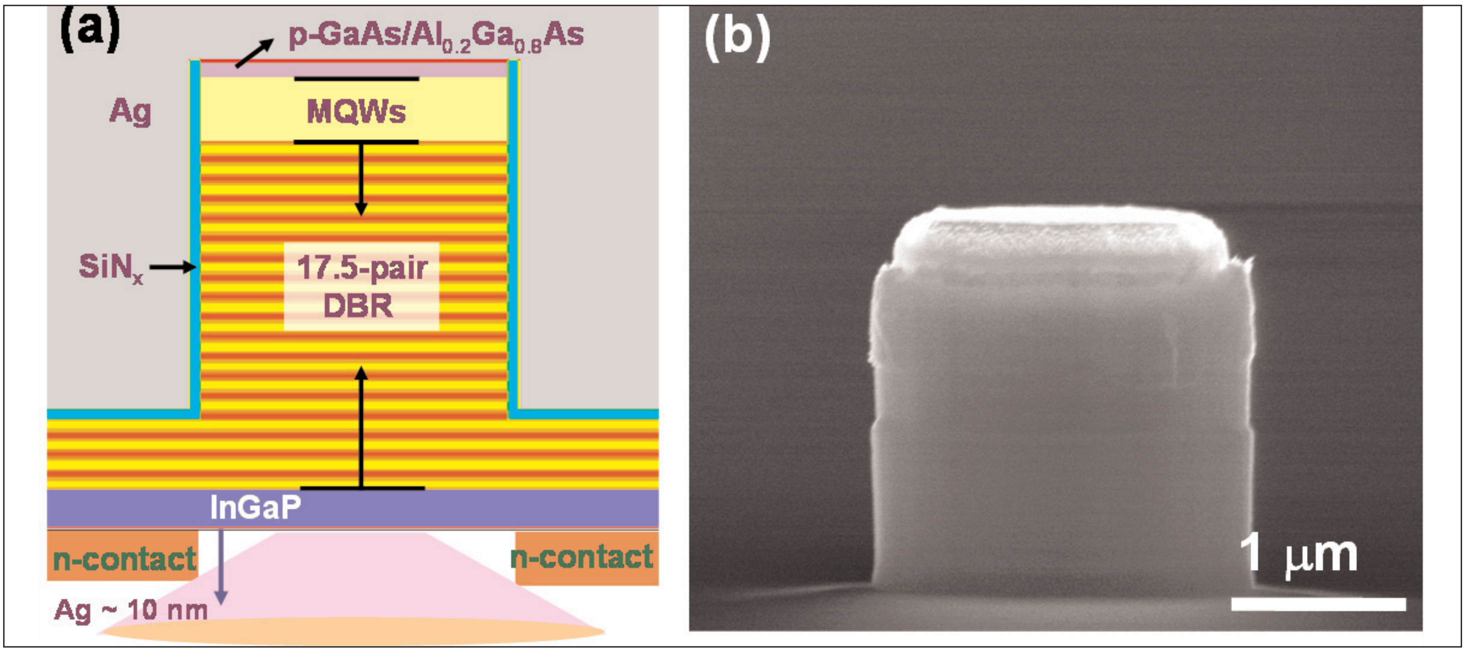

Figure 2. (a) University of Illinois at Urbana-Champaign/TU Berlin metal-cavity surface-emitting laser device flip-chip bonded to silicon that supports the contact and serves as heatsink. The physical size of the device is 1.0µm radius and 2.5µm total thickness. (b) SEM of a metal cavity after silver metallization. (From [1].)

The 850nm wavelength VCSEL presently constitutes the largest volume, with tens of millions of diodes being produced per month. The main applications for these devices are short-range (up to 300m) high-speed high-capacity optical data links (multi-mode optical fiber in data centers and computer clusters) and optical computer mice.

Local (LAN) and storage (SAN) area networks already exist that use 850nm VCSEL illumination. Further protocols for 850nm VCSELs are being developed such as Fiber Channel FC32G, InfiniBand, and universal serial bus (USB).

The monolithic 850nm VCSEL (Figure 1) depends on a particularly fortuitous combination of refractive index/bandgap in the aluminum gallium arsenide (AlGaAs) system. In particular, the top and bottom mirrors are created as distributed Bragg reflectors (DBRs) consisting of a large number of AlAs/GaAs quarter-wavelength pairs.

Fabrication processes have been developed for both molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). These processes need to deliver up to 100 layers of different material compositions with better than 2nm thickness control.

Production techniques for 850nm devices have tended to be MOCVD, since it is far easier to grow graded material compositions as needed for the DBR interfaces. However, recent developments have enabled MBE to produce multi-step grading. Also, large platens capable of holding a number of substrates have increased throughput. MBE also has advantages for growing a wider range of compound semiconductor compositions on GaAs substrates, as needed for moving away from the 850nm wavelength.

The technology that makes monolithic devices at 850nm possible is not directly transferable to other wavelengths. Non-monolithic approaches (wafer bonding, dielectric mirrors, metamorphic mirrors, MEMS) are more difficult and, therefore, expensive.

Extending the monolithic nature of the 850nm technology to a wider band of wavelengths (650–1550nm) is therefore very attractive. And, with a broader wavelength palette, new applications come into view: fiber-to-the-home, biomedical sensors for tracking the efficacy of medical therapies, ultra-high-density optical storage, large-area, nano-scale inspection, and so on.

AlAs/GaAs DBRs suffer from a smaller refractive index contrast at shorter wavelength. Varying the 850nm design to accommodate shorter wavelength requires a larger number of quarter-wavelength layers in the DBRs, and the p-DBR is particularly difficult to create with low enough resistance. Also, the thermal conductivity of the graded AlGaAs interfaces decreases, creating thermal management problems for these devices.

Long-wavelength VCSELs have been enabled by the development of GaInNAsSb and InAs quantum dots, allowing 1300–1550nm devices to be created. However, DBR limitations arise here also, along with free-carrier absorption and high series resistance of devices.

Longer wavelengths such 1550nm are particularly attractive due to lower voltage operation and hence lower power consumption, resulting from the narrower bandgap used in the active layers. Also, the transmission of 1550nm in silicon is particularly favorable. Intra-chip connections with silicon waveguides could take advantage of this. Plus, the 1550nm range has

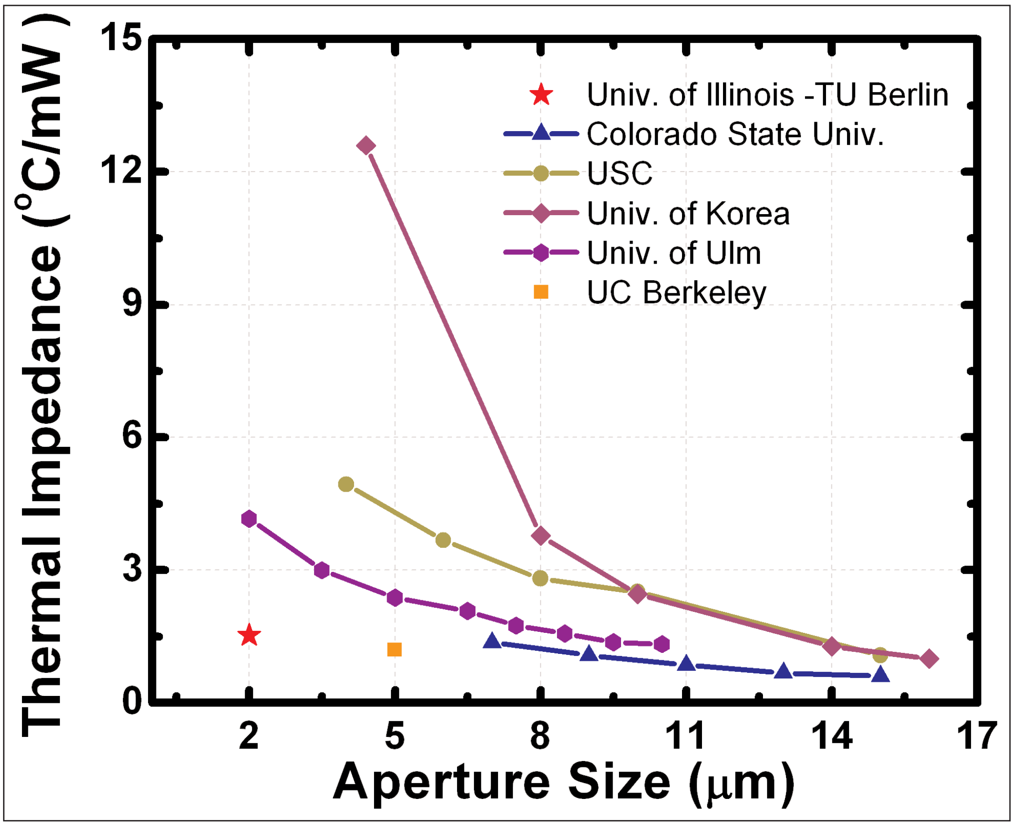

Figure 3. Comparison of thermal impedance as a function of aperture (diameter) size for various VCSELs presented in the literature and for Univ. of Illinois–TU Berlin's metal-cavity surface-emitting laser (star). The thermal impedance of 1.327°C/mW for the metal-cavity device is comparable with those of VCSELs having apertures as large as 10μm.

already been widely developed for 1550nm (1.55μm) with metro-range links of 10–20km and, of course, the best performance of long-distance (hundreds of kilometers) silica-based optical fiber is often centered on this wavelength. Other 1550nm possibilities include free-space optical data transmission and light detection and ranging (LIDAR or 'laser radar').

Fiber-to-the-home is based on 1310nm (upstream) and 1490nm or 1550nm (downstream) lasers. To be cost effective, these devices must avoid complicating factors like cooling systems, optical isolators or external modulation. To compete with mobile network offerings, these systems will need to handle HD TV, high-resolution imagery, etc.

Apart from telecoms, VCSELs could be monolithically combined with other optical or optoelectronic elements such as detectors, thin-film filters and gratings. One area where integrated devices could be used is biomedical analysis (bio-defense, drug development, in-vivo imaging, diagnostics, etc.). Here one needs miniature, disposable device arrays.

Wide-ranging portfolio

Institut für Festkörperphysik und Zentrum für Nanophotonik at Technische Universität Berlin (TU Berlin) has perhaps one of the widest-ranging portfolios of high-performance VCSELs and metal-cavity surface emitting lasers, developed in conjunction with a number of other organizations.

In their latest joint work, University of Illinois at Urbana-Champaign and TU Berlin have produced metal-cavity devices (Figure 2) that are flip-chip bonded to a gold-coated silicon substrate [1]. Metal-cavity devices are a variation on the VCSEL that have attractive features including shielding of neighboring devices from cross-talk and efficient heat removal due to the use of high-thermal-conductivity metal, enabling better thermal management. This latter quality is especially important for ultra-small devices under high current injection.

Thermal effects limit modulation speed and cause gain saturation in short-cavity devices such as VCSELs. Also, the smaller-aperture devices allowed with metal cavities should lead to higher modulation bandwidth.

The metal cavities consisted of silicon nitride (SiN) dielectric coated with silver and then gold (to prevent oxidation). The optical confinement comes in the form of surface-plasmon waves in a thin skin at the metal/dielectric interface. To reduce thermal effects to a minimum, the substrate was removed from these devices.

A 2μm device had a thermal impedance value as low as 1.327°C/mW and a small thermal wavelength shift of 4.367x10^{-2}nm/°C. VCSELs have higher values (Figure 3), with a recent 10μm aperture device managing to exhibit a thermal impedance of 2°C/mW.

Although the quality factor of metal-cavity devices is lower than that for the dielectric confinement of VCSELs, the metal devices tend to have shorter photon relaxation times, allowing for greater modulation speeds.

TU Berlin has also worked with Berlin-based firm Vertically Integrated Systems (VI Systems) on 980nm VCSELs [2]. The longer wavelength has advantages for very-short-reach applications such as next-generation board-to-board, module-to-module and chip-to-chip interconnects.

In particular, the 980nm wavelength is absorbed more readily by silicon photodetectors, compared with 850nm illumination. Such devices could also be used with active optical cables (AOCs) designed for the 980–1100nm wavelength range.

Other favorable features include lower operating voltage and greater transparency of the GaAs substrate at 980nm. These attributes allow greater freedom in device design and packing density of VCSEL arrays powering high-density interconnects. The 980nm light can be used with polymer waveguides because of absorption and dispersion properties at these wavelengths.

However, there are problems operating at 980nm, such as strict control of doping to avoid excessive free-carrier absorption, as well as strain effects in the active layers. Since 980nm devices are likely to be used in very-short-reach data links that could be located near hot microprocessors, thermal management is again a particular concern.

TU-Berlin/VI Systems have increased error-free ($<10^{-12}$ bit error rate) bit rates at 85ºC from less than 20Gbit/sec to 25Gbit/sec, bringing these devices up to the achievements of 850nm and 1100nm VCSELs at high temperature.

The 85ºC tests were performed without adjusting the drive current or peak-to-peak voltage. Such adjustments complicate drive circuitry and increase total power consumption. The devices were grown

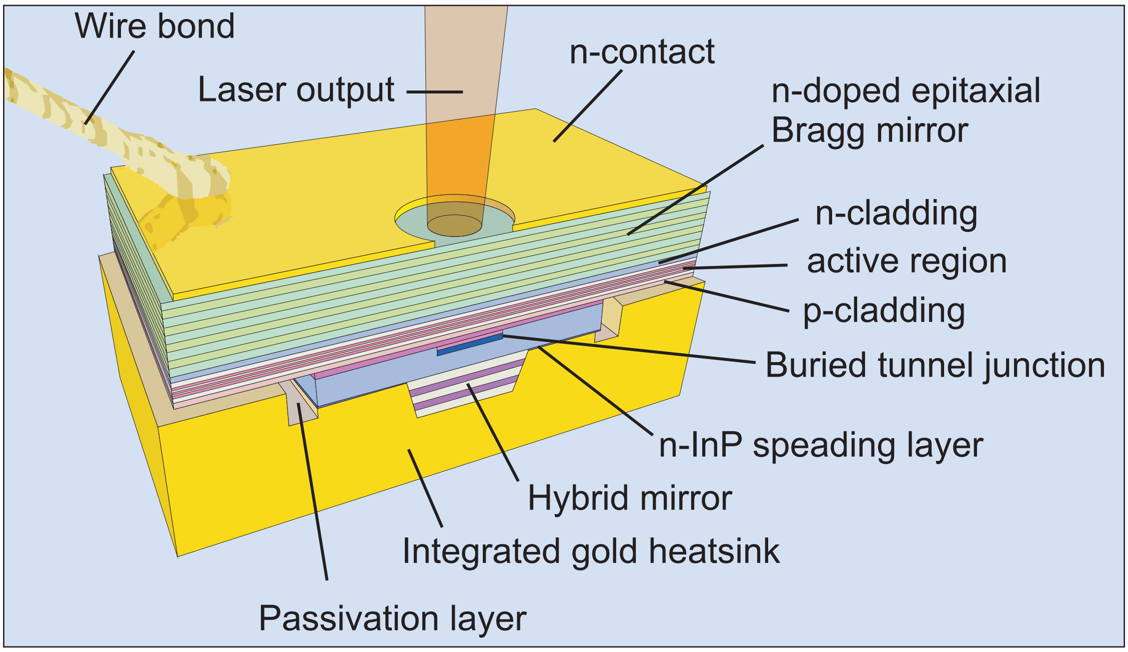

Figure 4. Indium phosphide-based long-wavelength (LW) VCSEL. A buried tunnel junction (BTJ) serves as a current aperture. Gold is used as a bottom reflector (within a hybrid mirror) and a heatsink. A wavelength range of 1.3–2.3μm can be covered by this technology. The device was optimized for continuous wave (CW) operation.

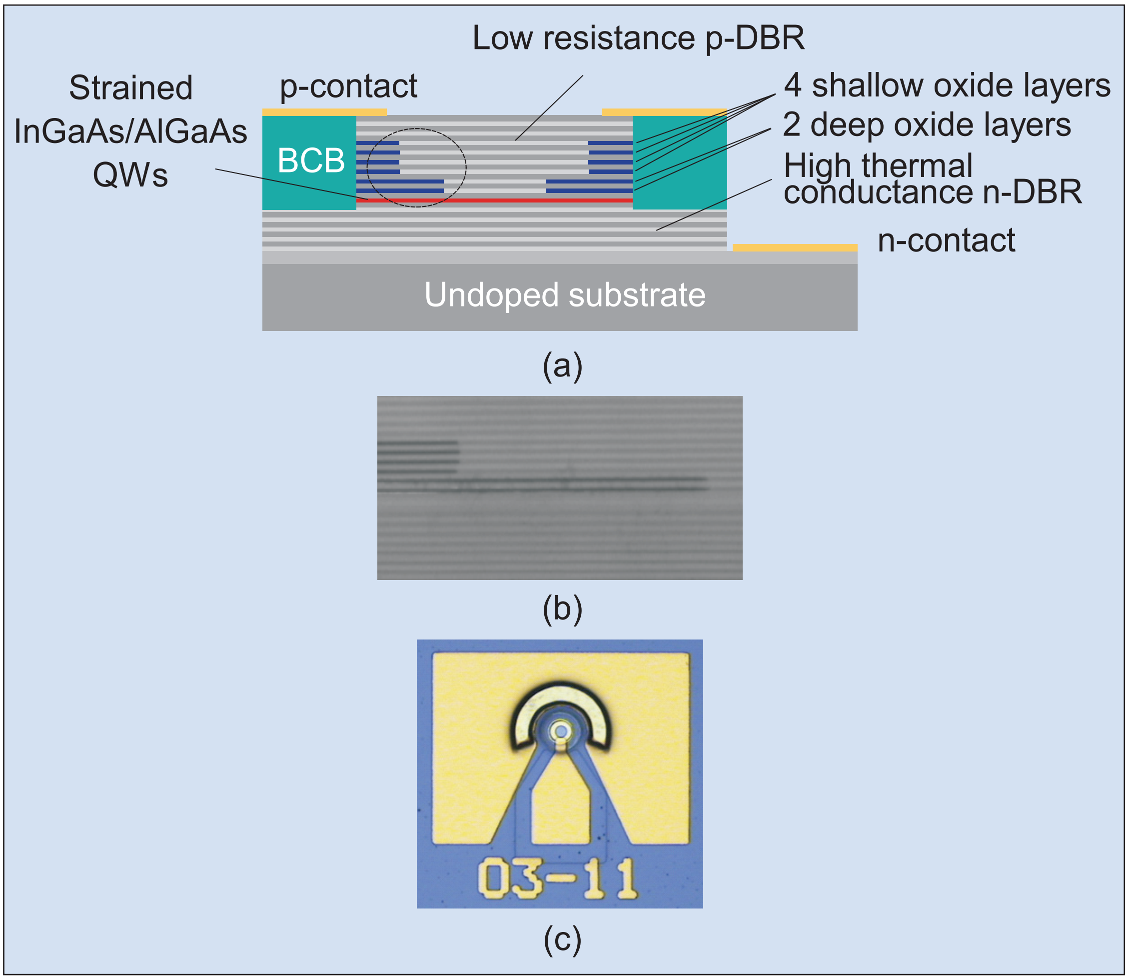

Figure 5. (a) Cross section of Chalmers 850nm VCSEL design, indicating several of the design features for high speed. (b) SEM of the oxide layers (within the area indicated in (a)). (c) Microscope image of the high-speed VCSEL chip showing the ground–signal–ground contacts for high-frequency probing.

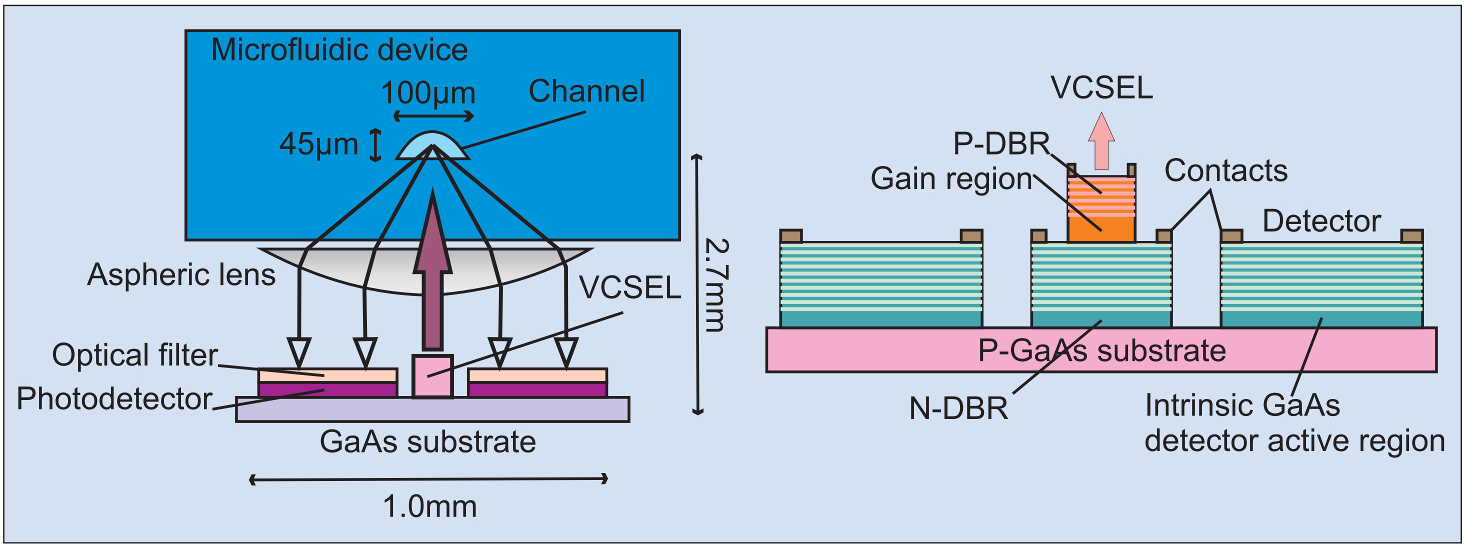

Figure 6. Stanford sensor architecture for 773nm integrated sensor designed for microfluidic applications (left), and the monolithic epitaxial structure to realize such a sensor with the VCSEL bottom DBR used as a fluorescence emission filter (right).

using mature and proven mass-production MOCVD and conventional quantum well designs.

Among the features used to make the VCSEL insensitive to temperature shifts was to detune the quantum well photoluminescence peak and cavity resonance by 15nm. This was designed to compensate for gain decreases at high temperature. As a result, the minimum threshold current was observed at 50ºC. In the 20–85ºC range, the threshold deviates from the minimum by less than 16%. The low threshold current contributes to maintaining the large differential gain that is needed for high-speed operation.

The maximum bandwidth at 20ºC was 15.3GHz, decreasing by only 2GHz to 13.2GHz at 85ºC. The received optical power for the lowest bit-error rate was less than −1dBm (794µW). The power penalty for working at 85ºC (rather than 25ºC) is 0.8dB (1.2x).

Analysis suggests that the dominant speed-limiting factors for the present devices were limited heat dissipation and damping effects. The 980nm research was carried out as part of the European Commission's framework 7 (FP7) project Vertically Integrated Systems For Information Transfer (VISIT) [3].

TU Berlin researchers have also produced 1530nm VCSELs capable of 40Gbit/sec modulation, based on indium phosphide technology [4]. The error-free data rate was somewhat lower at 35Gbit/sec at room temperature (25Gbit/sec at 55ºC). This improved on a design that achieved error-free 25Gbit/sec data rates.

To achieve the 35Gbit/sec performance, the top mirror design was optimized and the manufacturing process improved to give higher yields. The resulting chip has coplanar contact pads, low internal chip capacitance, reduced cavity length, and high single-mode power (2.5mW with 5µm aperture).

Higher data transmission rates of 40Gbit/sec were possible for short pseudo-random bit-sequences (PRBSs) of 2^7-1. But for longer sequences, bit-error rates increased; this is attributed to very thin epitaxial layers very close to the active region with poor thermal conductance and thermal time-constants in the low GHz-range.

Another approach being followed at TU Berlin is using buried tunnel junctions to create lower-resistance p-type contacts [5]. The tunnel junction allows a p-type contact to be connected with lower-resistance n-type material (Figure 4).

40Gbit/sec error-free at 850nm

Chalmers University of Technology in Sweden is among the many other organizations developing VCSELs. Among its latest achievements has been a high-speed multi-mode 850nm VCSEL with 40Gbit/sec error-free operation with less than 0dBm (1mW) of received optical power and small-signal modulation bandwidth of 23GHz [6]. The researchers comment: "This is the first demonstration of 40Gbit/sec error-free operation of an 850nm VCSEL."

The Chalmers team turned to TU Berlin for help with the 40Gbit/sec measurements. The Tyndall Institute in Ireland contributed expertise to the active region design. IQE Europe supplied the epitaxial material.

The bandwidth was maximized through a series of factors affecting the active region, mirrors and oxide layers (Figure 5). The active region (5x strained InGaAs/AlGaAs quantum wells) was designed with a large differential gain and small gain compression (non-linearity). A low-reflectivity top-mirror (22-pair DBR) reduced the photon lifetime. The oxide layers were used to reduce parasitic capacitance, along with providing optical confinement. Bond capacitance was controlled by putting benzocyclobutene (BCB) under a small bond pad. To reduce resistance, graded interfaces and modulation doping were used in the AlGaAs DBRs.

The resulting VCSEL (with photon lifetime of 3.3psec) had 0.43mA threshold current and 0.98W/A slope efficiency. Increasing the photon lifetime to 6.4psec (by varying the top layer thickness of the p-DBR) gives a lower threshold of 0.28mA but also a lower slope efficiency of 0.46W/A.

The series resistance of the device (130Ω) is described as being relatively high. An 'accidentally high contact resistance' is blamed. The researchers believe that the performance of the device could be improved with lower series resistance to give a few extra GHz of modulation bandwidth.

Widening the application net

Stanford University researchers see a number of possible applications for VCSEL outside of data comms [7]. For example, Stanford has developed plasmonic nano-apertures to produce high optical intensity near-field illumination for sub-wavelength ultra-high-density optical storage, single-molecule spectroscopy, high-resolution imaging and high-throughput inspection.

In one application for such devices, the Stanford team has developed in-vivo monitoring devices for use in small animals (Figure 6). Presently, the VCSEL excitation sources operate in the near-infrared (NIR) range 750–1000nm, but it would be useful to cover a wider range of wavelengths.

Stanford's first in-vivo device (a fluorescence sensor) had a 773nm VCSEL monolithically integrated with a photodetector. The bottom-reflecting DBR of the VCSEL was also used to filter out the excitation light at the photodetector, allowing it to concentrate on fluorescence from the sample. The side lobes of the DBR transmit roughly 40% of the fluorescence from the fluorophore used (IRDye800 phosphoramidite in ethanol). Optical blocking layers were used to prevent cross-talk between VCSEL and sensor.

A more recent fluorescence sensor was based on a 675nm VCSEL (Figure 7) for deep red and NIR applications using fluorescent proteins and fluorophores. This device reversed the growth order between the VCSEL (first) and detector (second). This was to ensure a high-quality material structure for the more challenging shorter-wavelength AlGaInP VCSEL layers.

A further problem for in-vivo systems at shorter wavelength is thermal management, since it is not possible to include heat sinks. The 675nm device achieved 2mW multi-mode output power. The photodetector had a dark current density of less than 5pA/mm^2 with a reverse bias of up to 1V, and an internal quantum efficiency of more than 75%. The fluorophore Cy5.5 was sensed in concentrations as low as 5nM (5x10^{-9}Moles/liter) in vitro and 50nM in-vivo (limited by autofluorescence of animal tissue).

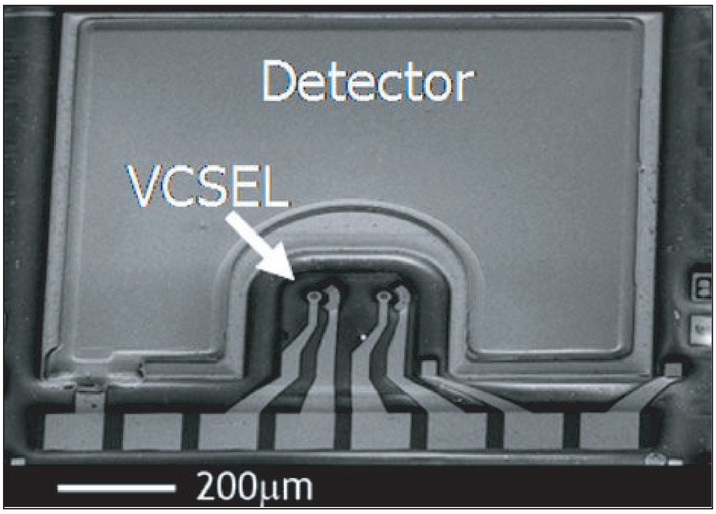

Figure 7. SEM of a single-pixel monolithically integrated fluorescence sensor with 675nm VCSELs and a thin-film emission filter, developed at Stanford.

Although LEDs could be used, VCSELs have higher output intensity and the directional nature of the beam reduces cross-talk. Also, the narrow spectral linewidth of VCSELs enables easier separation between fluorescence excitation and emission wavelengths.

Stanford has also combined 780–850nm VCSELs with photonic crystals and biomolecule capture layers, in efforts to create sensing without fluorescent labeling. The analyte is detected through changes in the index of refraction, affecting the guided resonance of the photonic crystal. Further scanning detection capabilities can be obtained by varying the VCSEL wavelength using changes in temperature or current.

Another possible way forward to more VCSEL applications has emerged in the past few years: high-power light sources (~100W) based on arrays of devices. The 100W level makes possible the use of brute laser power in applications such as cosmetics (hair/wrinkle removal), military/surveillance infrared light sources, pumping power sources for other solid-state/fiber lasers, production of green light through second-harmonic generation (SHG) frequency-doubling, and machining (cutting, drilling, ablation, engraving). ■

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