Tripping the light fantastic#2

Laser diodes – may the force be with you

Edison themes

14 September 2021

This report is the second in a series of three examining key growth areas in the global photonics market. It looks at laser diodes, tiny semiconductor lasers that are used for a growing range of applications including materials processing, data communications, biometric facial recognition and range-finding. Mordor Intelligence expects demand from these applications to drive global market growth at a CAGR of 11.2% between 2021 and 2026 to reach US$16.3bn by 2026.

A high-growth market

Historically, laser diodes have been used primarily for materials processing and high-speed data communications. In recent years demand from consumer and mobile applications, primarily related to the introduction of FaceID in the iPhone X in 2017 and of world-facing LiDAR for augmented reality (AR) apps in the iPhone 12 in 2020, has boosted market growth. Market analyst Yole Développement expects demand from the consumer and mobile segment to continue to grow as facial recognition and LiDAR functionality is adopted in a broader range of devices. Yole also expects continued growth in demand from data communications applications as well as strong growth from automotive applications such as range finding for autonomous vehicles, albeit from a low base.

Longer wavelengths challenge the status quo

The laser diode market is on the cusp of a key transition as OEMs look for longer wavelength laser diodes in order for LiDAR to be eye-safe and, in the case of mobile phones, able to be located under the OLED screen rather than in a cutaway. This shift is, in our opinion, likely to catalyse the adoption of novel compound semiconductor materials such as dilute nitrides. It is also likely to promote greater adoption of molecular beam epitaxy (MBE) for manufacturing the compound semiconductor wafers that are the foundation of laser diode chips. This report identifies some of the companies, such as **Riber (ALRIB: EPA)**, which are likely to benefit from this market transition.

Deploying technology to reduce costs

The report discusses techniques being developed by companies like **IQE (IQE:LN)** that will enable laser diodes to be manufactured on larger diameter wafers. Migrating to larger wafers reduces the cost of production per chip, potentially accelerating adoption in cost-sensitive consumer applications.

Deploying technology to improve output power

The report also describes a novel approach being developed by **BluGlass (BLG:ASX)** for improving the efficiency of high-power laser diodes. These higher-power devices are particularly suitable for applications such as 3D printing and materials welding.

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Companies mentioned in this report

- II-VI
- Aixtron
- Apple
- BluGlass*
- IntelliEPI
- IQE*
- Lumentum
- Riber*
- Veeco Instruments

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The laser diode market

Laser diodes are used in a growing number of applications that include cutting and welding, machine vision, data communications, range finding and medical diagnostic systems. These applications are categorised by wavelength in Exhibit 1. A report from Mordor Intelligence notes that the global laser diode market was valued at US$8.8bn in 2020 and predicts that the market will grow at a CAGR of 11.2% between 2021–26 to reach US$16.3bn by 2026. In this section we describe some key growth applications – data communications, biometric facial recognition, range-finding and optical diagnostics – in more detail.

Exhibit 1: Laser diode applications and wavelength

Type	Wavelength	Application
Ultraviolet (UV)	200–400nm	Disinfection of water, air and surfaces (261nm, 265nm), defect inspection in semiconductor industry (261nm), exciting fluorescence in proteins and other bio-molecules (261nm), Raman spectroscopy used in chemistry to identify molecules (261nm), treatment of psoriasis (272nm), UV curing, flow cytometry calcium detection (349nm)
Blue-violet	405nm	Blu-ray disc and HD-DVD drives, 3D printing, detection of skin and oesophageal cancer
Blue	420–465nm	Automotive headlights, general lighting, spotlights/torches (450nm), welding copper (450nm), cutting/engraving (445–450nm), dentistry (420nm), optogenetics (420nm), photo-dynamic therapy (420nm), confocal microscopy (488nm), tissue cutting (420nm), detection of bilirubin (455nm), 3D printing (450nm)
Green	510–525nm	Visual alignment (520nm), laser projectors, detection of haemoglobin (575nm)
Red	630–700nm	3D scanning (635nm, 660nm), visual alignment (635nm, 650nm), bar code readers (670nm), CD and DVD drives (650–660nm)
Near infra-red (NIR)	705–1400nm	Printing (780nm), 3D sensing (940nm) including biometric facial recognition (940nm), LiDAR (905nm), night vision systems (850–940nm, short distance fibre-optic communication (850nm))
Short wavelength infra-red (SWIR)	1,400–3,000nm	Long distance fibre-optic communication (1,064nm, 1,310nm, 1,550nm, 1,560nm), LiDAR (1,550nm), detection of glucose (1,650nm)

Source: Edison Investment Research

Data communications

Light passing down optical glass fibre is able to transmit much more data per second than electricity passing down copper wire. Moreover, wave-division multiplexing techniques enable a single fibre to transmit multiple beams of light, each of a slightly different wavelength, enabling a fibre optic cable to handle even more data and supporting the expansion of the internet that we have today. Until a decade ago, fibre optic cable was predominantly used for long-distance transmission and formed the backbone of communications networks. Over the last decade telecommunications companies have begun to deploy optical communications links connecting the fibre ‘backbone’ to end users. They have created networks variously referred to as fibre to the home, fibre to the premises or fibre to the curb to deliver triple-play services including TV, voice over IP phone and internet services to subscribers because of the higher data rates that they can deliver. Deployment of ‘last-mile’ links is driving demand for optical components.

Optical connections are also much more efficient with regards to energy consumption than their electronic counterparts. This means that they are being adopted in data centres, where power, including that required for cooling purposes, is a significant proportion of operating costs. Data centre capacity is being driven by 5G connectivity and the introduction of interconnected smart devices, referred to as the internet of things (IoT). Adoption of optical communications links in data centres is also helping drive demand for optical components.

Biometric recognition

Facial recognition applications use precise 2D or 3D measurements of a person’s face and head to verify their identity. The information is generally used to access an application, system or service, for example authenticating the user of a smartphone. Biometric facial recognition typically uses a structured light approach in which a fixed pattern of light is projected onto the face and the distortion to that pattern captured and analysed to create a reconstruction of the face. In the case of the FaceID system first deployed in the iPhone X in 2017 iPhones, up to 30,000 infra-red dots are projected onto the face and the distortion of the regular pattern of dots is captured by an infra-red camera and then analysed to construct a 3D representation of the face. A non-visible light wavelength is used so as not to be intrusive for the user. Typically 940nm is used because it is completely invisible to the human eye and suitable emission sources are readily available.

Range finding (LiDAR)

LiDAR (light detection and ranging) works by measuring the amount of time it takes for a pulse of light to be emitted, to bounce off a target and to be picked up by a detector and then uses that time to calculate how far away the target is. This is referred to as time of flight (ToF) detection. LiDAR technology is being adopted in a range of fields including machine vision, autonomous vehicles, gesture recognition, geographical mapping, incoming wind detection for wind turbines and military targeting. Typically an array of emitters and detectors is used to construct a 3D image of all the objects within the sensors' field of view. Significantly, the iPhone 12 Pro launched in October 2020 included a world-facing LiDAR scanner to improve AR experiences. The ability to integrate more accurate information about a handset user's physical environment into the AR world will potentially catalyse the launch of 'must-have' AR apps, encouraging other OEMs to incorporate LiDAR in their smartphones.

Exhibit 2: Video showing LiDAR in iPhone 12

Source: Youtube

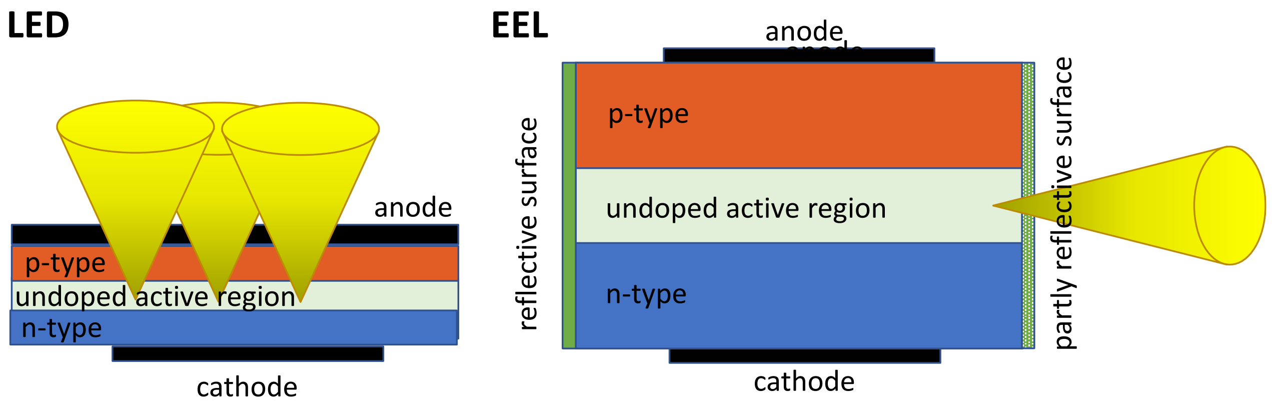
The longer the distance covered by the LiDAR, the stronger the emitted beam of light needs to be. The iPhone12 emits laser beams that can reach around 5m. It uses light in the near infrared (NIR) region of the electromagnetic spectrum (905nm) because laser diodes operating at this wavelength are relatively inexpensive. However, the human eye is sensitive to this wavelength, posing safety issues if more powerful beams at this wavelength are used to cover the longer distances required for automotive LiDAR applications. This is being addressed by using longer wavelengths of light (1,550nm) in the short wave infrared (SWIR) part of the spectrum, which do not damage the eye at high powers. Using longer wavelength light also means that the LiDAR scanner in a smartphone can be located underneath the OLED screen, eliminating the need for a cutaway or notch.

Optical diagnostics

Optical diagnostic systems provide a way of monitoring a patient's condition without having to take samples of blood. The systems send pulses of laser light through a patient's skin and measure the amount of absorption and scattering that has occurred. The light can be tuned to a specific wavelength for detecting the levels of different molecules in the patient's blood: 575nm for haemoglobin, which indicates the amount of oxygen in the blood; 455nm for bilirubin, which indicates liver function; and 1,650nm for glucose, which helps diabetics monitor the amount of insulin required. Tuning is done by modifying the proportion of different elements forming individual layers of the compound semiconductor wafers used to make laser diode chips.

Laser diode choices

Exhibit 3: Simplified LED and edge-emitting laser (EEL) structures



Source: Edison Investment Research

As discussed in the first report in this series, a light emitting diode (LED) emits light when an electron from the n-type layer (shown as blue in Exhibit 3) absorbs energy from an external electric field so it is in an excited state and then recombines with a hole (or anti-electron) from the p-type layer (shown as red in Exhibit 3) so that the electron and hole cancel each other out and the electrical energy is emitted as a particle of light or photon. This is known as spontaneous emission. An LED emits light across its surface, forming an unfocused beam.

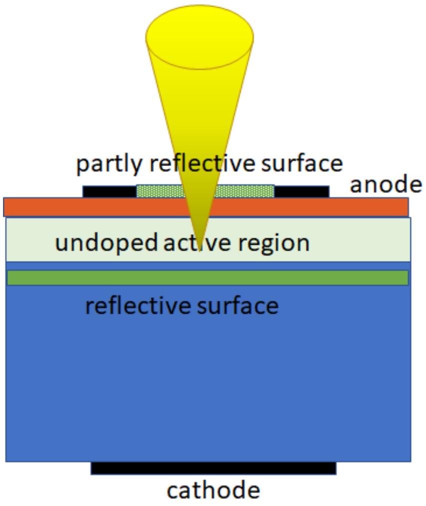
Stimulated emission creates a powerful, focused light beam

A laser diode has an undoped region between the p-type and n-type layers where holes and electrons collect. The light emission process is similar to an LED to start with, as an excited electron and hole combining to create a photon. However, the emitted photon is trapped inside the active region by extra layers of compound semiconductor material termed waveguides, which are above and below the active layer, and is bounced between the mirrored surfaces at each edge of the active layer. When one of the photons formed by spontaneous emission meets an excited electron (one that has absorbed energy from the electric field) before it has had time to recombine with a hole, the electron absorbs the light energy from the photon as well as the electric energy and emits two photons travelling in the same direction when it eventually recombines with a hole. These two photons are trapped inside the active region and generate more photons, which bounce between the mirrors hundreds of times, generating more and more photons, eventually producing a narrow beam of high-intensity light powerful enough to escape through the partly reflective surface. This is known as stimulated emission. Stimulated emission produces a beam of light that is much more powerful and focused than light from an LED and which can be switched on and off much more quickly (see Exhibit 5 for a comparison of LEDs and laser diodes.

Edge-emitting lasers versus VCSELs

Lasers where the beam is emitted from one of the sides are referred to as edge-emitting lasers (EELs). Alternatively the mirrors can be constructed above and below the active areas using multiple layers of compound semiconductor materials, so the light beam is emitted from the top surface of the structure. This type of laser (Exhibit 5) is referred to as a vertical cavity surface emitting laser or VCSEL.

Exhibit 4: Simplified VCSEL structure



Source: Edison Investment Research

Cost advantages of VCSELs

As EELs emit light from the side, they cannot do this until the epitaxial wafer containing the laser diode structure has had the metalisation layers creating the contacts to the diodes added and the wafer has been cut up into time chips, exposing the side edges from which the light is emitted. This means that the laser diodes cannot be tested until this point. Since VCSELs emit light from their top surface, they can be tested prior to the packaging step, which substantially reduces the production cost compared with EELs. In addition, although an individual VCSEL is typically substantially lower power than an EEL, VCSELs can be fabricated into devices with high density arrays of emitters that collectively output a high-power beam tuned to a specific frequency These arrays have applications in industrial illumination, 3D printing, drying and curing plastics and sintering metals. Until 2017, the VCSEL market was driven by short-range datacom applications in data centres, enterprise and campus networks. Since 2017, 3D sensing has become the dominant application, especially since **Apple (AAPL:US)** began to use FaceID in the iPhone X.

Yole Développement's report on the VCSEL market published in July 2021 predicted that mobile and consumer applications will represent around 64% of overall VCSEL revenues in 2021. Fixed telecommunications and infrastructure will represent 34%. The report predicts that the global VCSEL market will grow from US$1.2bn in 2021 to US$2.4bn in 2026, which equates to a 13.6% CAGR over the forecast period. Yole expects that market growth overall will be driven by mobile and consumer applications, which it predicts will show a 16.4% CAGR over the forecast period. Automotive and mobility applications are expected to demonstrate a 121.9% CAGR over the period, though from a relatively low base of only US$1.1m in 2021. Medical applications are expected to demonstrate 32.4% CAGR over the forecast period but from a base of only US$0.5m in 2021.

The Yole report notes that the VCSEL market is dominated by two companies, **Lumentum (LITE:US)** and **II-VI (IIVI:US)**, which held shares of 42% and 37% respectively in 2020. Both companies supply VCSELs used in iPhones. Lumentum outsources production of compound semiconductor epiwafers. Industry sources infer this is to IQE. II-VI manufactures epiwafers in-house following the acquisition of Finisar, which completed in September 2019. Apple invested US$390m in Finisar in December 2017 to create a 700,000-square-foot VCSEL manufacturing plant in Texas. In May 2021 Apple announced a further US$410m investment in the parent company, II-VI.

Edge-emitting lasers for higher powers

Although VCSELs are preferred to EELs because of their relative cost, they are not suitable for all applications. EELs are required for higher power applications where it not appropriate to use an array of VCSELs to achieve the same power output. In addition, while the lower efficiency of VCSELs is not significant for lower power applications, given that the waste energy is converted to heat, the difference becomes important at higher power outputs. The problem of waste heat is particularly problematic for VCSELs because the structure means that the p-side, which generates light and heat, is not in direct contact with a heat sink because the reflective mirror layers get in the way so the heat accumulates. In contrast the p-side of an EEL can be directly bonded to a heat sink, improving thermal dissipation and reducing the occurrence of localised overheating. EELs may be used on their own and also coupled with optical fibres or crystals to make higher-powered fibre lasers or diode-pumped solid-state lasers.

In a report published in May 2021 Yole Développement predicted that the global EEL market would grow from US$2.9bn in 2020 to US$6.6bn by 2026, a CAGR of 15%. Currently optical communications and materials processing applications account for over 75% of the market. Yole expects most of the market growth to come from the optical communications segment, which it predicts will grow with a CAGR of 18% over the forecast period. It expects that emerging applications such as display, sensing, medical and lighting will show a CAGR of 15%.

Exhibit 5: VCSELs, EELs and infra-red LEDs compared

	Infra-red LED	VCSEL	EEL
Power (continuous wave)	~4W – scales with area	~ 8W – scales with area	Designed for pulse operation
Power (pulsed)	Not designed for pulsed operation	~120W – larger area	~120W – point source
Power density	1–5 W/mm^2	Few 100W/mm^2	60kW/mm^2
Beam quality	Very wide divergence ± 60deg	Symmetric low divergence ± 10 deg (round pattern)	Asymmetric low divergence ± 5deg × 12deg (elliptical pattern)
Wall-plug efficiency	30–40%	35%	45%
Temperature shift	0.25nm/K	0.07nm/K	0.25nm/K
Thermal dissipation	High	Low	High
Spectral width	20–30nm	1–4nm	3–8nm
Switching time	10–100ns	< 1ns	< 1ns
Cost	Low	Low-medium	Medium-high
Typical applications:	Specialist lighting, eg horticulture, simple gesture recognition	Short- and mid-range LiDAR, complex gesture recognition, 60–300m data transmission	Short-, mid- and long-range LiDAR, 2–40km data transmission, materials processing

Source: Arima Lasers, Osram OS, Edison Investment Research

Technical developments

Moving to longer wavelength VCSELs

As noted above, there is demand from OEMs to shift from NIR (905nm, 940nm) to longer SWIR wavelength (1,500nm) VCSELs so LiDAR can be made eye-safe and, in the case of mobile phones, may be located under the OLED screen rather than a cutaway. There is also interest in longer-wavelength VCSELs for data communications applications, which typically use EELs operating at 1,300nm at present. This is because the light beam from an EEL is elliptical and thus requires coupling optics to connect it to an optical fibre. A VCSEL emits a circular beam, so can dispense with the coupling optics, reducing costs.

Manufacturing InP VCSELs is technically challenging

This transition to longer SWIR wavelengths is not trivial. Typically, VCSELs for 940nm applications are formed on gallium arsenide (GaAs) wafers with both the active region and the reflecting mirrors made from adding dopants to the GaAs to modify its electrical properties. Longer-wavelength VCSELs are typically formed on indium phosphide (InP) wafers. There are issues with making effective reflective mirrors that will work with an InP active region, resulting in impaired signal modulation. This means that no one has begun to manufacture longer wavelength VCSELs in high volume yet.

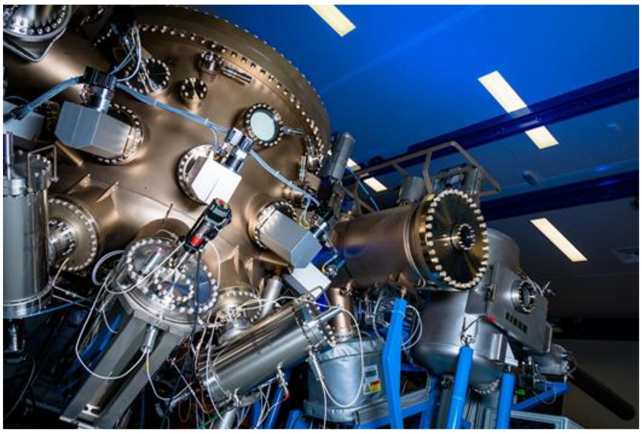
Dilute nitride technique improves performance

One approach that is being explored for SWIR VCSELs as an alternative to using InP related materials is the addition of small amounts of nitrogen to a gallium indium arsenide (GaInAs) active layer formed on a GaAs substrate. Using a GaAs substrate means that the structure can also incorporate high-performance GaAs-based reflective mirrors, addressing the signal modulation issue. The 'dilute nitride' approach also means that the longer-wavelength VCSELs can be manufactured on 150mm GaAs wafers thus improving production economics.

Epitaxy specialist IQE has been involved in the development of dilute nitride materials for nearly 20 years, having originally developed the technology to improve the performance of power amplifiers used in handsets. In March 2021 IQE announced that it had achieved key power (~1mW per emitter) and reliability (more than several hundred hours) milestones for its IQDN-VCSEL for advanced sensing applications at longer wavelengths on a 150mm GaAs substrate. The results met the development requirements for multiple Tier 1 3D sensing customers. IQE is currently engaged in customer-funded development programmes with key Tier 1 customers to refine this technology for qualification in future 3D sensing applications. Because IQDN-VCSEL is based on the GaAs materials system, it offers a longer wavelength 'drop in' solution for IQE's customers, enabling them to use the same equipment and processes that were developed for shorter wavelengths to achieve longer wavelengths (for more information, see Edison's research on IQE).

Longer wavelengths favour MBE adoption

Exhibit 6: MBE system for volume production



Source: Riber

Exhibit 7: MBE process control software

Source: Riber

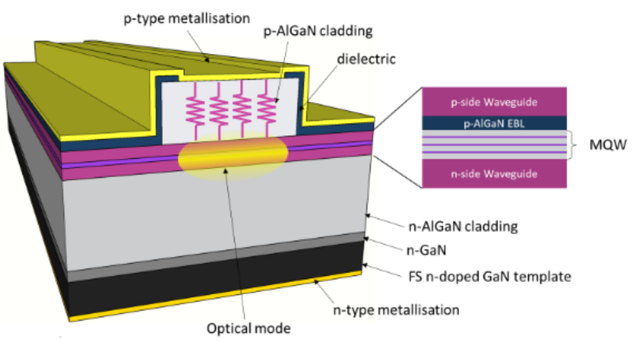
The shift to longer wavelengths has implications regarding the highly specialist equipment required for manufacturing VCSEL epiwafers. Typically VCSELs are manufactured using metal organic chemical vapor deposition (MOCVD) equipment from Aixtron (**AIXA:ETR**) or Veeco Instruments (**VECO:US**). This is because MOCVD is a relatively fast way of depositing the hundred different layers of compound semiconductor material forming a VCSEL. For example, IQE is currently using MOCVD reactors at its facility in Newport to provide high volumes of NIR VCSELs. However, the structures required for SWIR VCSELs require the greater control of deposition provided by molecular beam epitaxy (MBE) systems.

Wider adoption of MBE technology is clearly favourable for established equipment manufacturer Riber (see Edison research on Riber), which is the dominant supplier of MBE systems (Veeco has a much smaller market share). In April 2021 Riber announced that it had delivered the world's largest MBE system to long-standing customer **IntelliEPI (4971:TT)** for VCSEL applications. This machine has capacity to grow up to eight 150mm wafers simultaneously and offers the possibility of transitioning to 200mm wafers. The new system will augment IntelliEPI's installed base of 15 MBE systems, all from Riber. These MBE systems, including the new delivery, can be used for making NIR and potentially for SWIR VCSELs.

The transition is particularly favourable for epitaxy manufacturer IQE, which already has the largest installed base of MBE systems globally and many years of experience of the technology. IQE is in the process of consolidating its US MBE operations onto its North Carolina site where it has created a new Centre of Excellence for high volume MBE epitaxy to serve a wide range of photonics customers and technologies globally. These systems could potentially be used for SWIR VCSELs if the technology shifts to volume production.

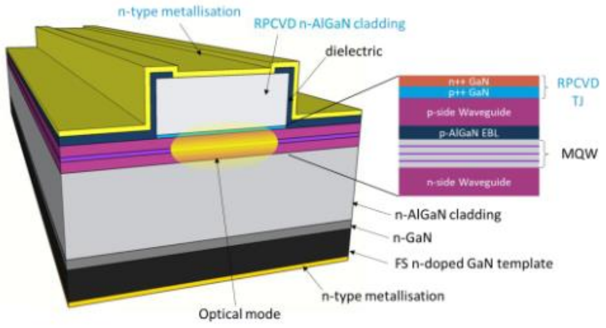
Making more efficient higher power laser diodes

Exhibit 8: Conventional laser diode manufactured using MOCVD technique



Source: BluGlass

Exhibit 9: Tunnel junction laser diode



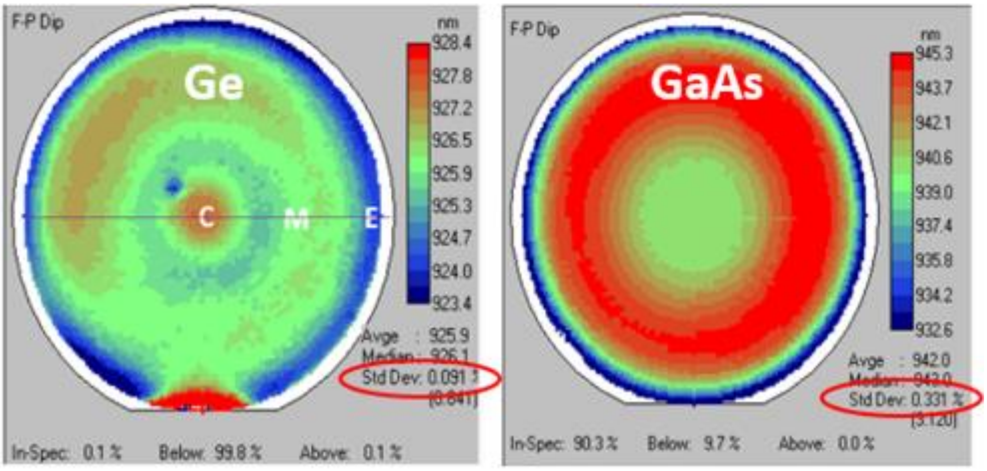
Source: BluGlass

Gallium nitride **(**GaN) is a compound semiconductor material typically used for high-power applications. GaN laser diodes, which are used for applications such as 3D printing and industrial welding, have conversion efficiencies of 40–45%. This compares poorly with GaN-based LEDs which achieve a conversion efficiency of almost 90%, suggesting that higher efficiencies may be possible. The waste energy in laser diodes becomes heat, limiting device performance. In addition, being able to manufacture more efficient laser diodes brings cost advantages, because the wafer area required for the same light output becomes smaller, enabling more devices at the same power output to be manufactured on a single wafer. One of the main reasons for the low efficiency of GaN laser diodes is significant optical and electrical resistive losses in the p-GaN waveguide and cladding layers above the multi-quantum well (MQW) structure where electrical energy is converted to light (see Exhibit 8). Australian technology company BluGlass is using its patented low-temperature, low-hydrogen remote plasma chemical vapour deposition (RPCVD) process to grow a tunnel junction on top of the MQW structure (Exhibit 9). This allows the p-type cladding to be replaced with n-type cladding, which has an inherently lower electrical and optical resistance. In August 2021 BluGlass successfully demonstrated the world's first working tunnel junction laser diodes manufactured using RPCVD. (For more information, please refer to Edison's research on BluGlass.)

Better economics from larger substrates

Moving from a 100mm wafer to a 200mm wafer increases the total wafer area by four times and the usable area by five times, potentially reducing the cost per laser diode chip by 25%. When IQE became the first company globally to manufacture shorter wavelength (940nm) VCSELs on 150mm wafers in 2014, it gave the company a significant cost advantage over its competitors as well as making it more attractive for OEMs to incorporate VCSELs into consumer devices. In November 2020 IQE announced that it had demonstrated device performance parity between identical (shorter wavelength) VCSEL structures grown on germanium (Ge) and GaAs substrates. This is important because it is difficult to grow VCSELs on 200mm GaAs substrates since the wafer bows during processing. (In April 2021 wafer manufacturer AXT (AXTI:US) announced that it had shipped its first 200mm diameter GaAs) substrates to a major customer, noting demand for high volume applications such as VCSELs and micro-LEDs) but the performance of any devices formed on these substrates has not been disclosed.) Using germanium removes this limitation, giving a processed wafer that is ~10x flatter. This simplifies the subsequent wafer fabrication process and results in a wafer that is up to ~3x more uniform (see Exhibit 10), providing additional design flexibility for the thicker device architectures required to create longer-wavelength VCSELs. Moving from a 100mm wafer to a 300mm wafer potentially reduces the unit cost by 40%. In the longer term IQE envisages growing VCSELs on germanium-on-silicon templates, giving a route to processing VCSELs on 300mm silicon wafers.

Exhibit 10: Side by side growth of VCSELs on germanium and GaAs



Source: IQE

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