Tripping the light fantastic #1

Micro-LEDs – small is beautiful

Edison themes

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This report is the first in a series of three examining key growth areas in the global photonics market. It looks at micro-LEDs, which are miniature light sources that are beginning to be deployed in both large displays such as video walls and smaller displays used in smart watches, smart phones and AR/VR headsets. Demand for these devices, according to Market Data Forecast, is expected to drive global micro-LED market growth at a CAGR of 80% between 2021 and 2026.

A high-growth market

Large displays based on micro light emitting diode (LED) technology are being adopted as an alternative to organic LED (OLED) displays. Micro-LED displays potentially offer better contrast, response time, colour range and lifetime, though they are currently substantially more expensive. Micro-LED technology is also being proposed for smart watches, smart phones and augmented reality (AR) or virtual reality (VR) headsets where both the lower power consumption and high brightness offered are attractive characteristics.

On the cusp of commercialisation

Konka, LG Electronics, Samsung and Sony have all launched tiled micro-LED displays with dimensions as large as 236”. These displays are still very high-end. In December 2019, Konka noted a price of around $240,000 for its 118" 4K configuration and $1.25m for its 236" 8K configuration. Technology deployment in displays for wearables is less advanced. MicroLED-info notes that the world’s first micro-LED watch was demonstrated by Konka in December 2020, though it did not say when the watch was likely to be commercially available. This report discusses both companies involved in manufacturing the electronic devices and semiconductor specialists involved earlier in the supply chain.

Manufacturing challenges are being overcome

Various technological solutions are being developed to cut the cost of manufacturing micro-LED displays, thus encouraging adoption. These include techniques for incorporating micro-LEDs into displays more efficiently and for reducing the cost of manufacturing the LEDs themselves. There is also significant development work ongoing in improving the brightness of LEDs for wearable displays. We note the potential for good returns for those companies that can solve these technical challenges.

Semiconductor equipment manufacturers

We conclude this report with a review of the semiconductor manufacturing technologies required for making micro-LEDs and the principal companies involved. These companies serve other markets as well, reducing the risk associated with investment in a market at a relatively early stage of growth.

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Companies named in this report

Advanced Micro-Fabrication Equipment
Aixtron
Allos Semiconductors
Apple
BluGlass*
China Star Optoelectronics Technology
Ennostar
Epistar
glō.
Konka
Leyard Opto-Electronic
LG Electronics
LuxVue
Nanosys
PlayNitride
Plessey Semiconductors
Riber*
RiTDisplay
Rohinni
Samsung Electronics
Sanan Optoelectronics
Soitec
SPAC GigInternational1
Sony
TCL Technology Group
Veeco Instruments
X-Celeprint
Xtrion

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What are micro-LEDs used for?

Micro-LED applications

A micro-LED emits no light at all when the electric field across it is off (see Exhibit 2), so the contrast between light and dark is much better than a liquid crystal display (LCD) pixel, which will still let a little light from the backlight through when it is in 'off' mode. As a result, arrays of micro-LEDs are being adopted as a technique for improving the colour contrast and colour saturation of flat panel displays, with each micro-LED forming a single pixel in the display. Micro-LED technology also potentially offers better response time, power consumption and lifetime than OLED technology, though it currently substantially more expensive (see below). In addition, the improved energy efficiency makes micro-LED technology a desirable alternative to conventional LCD technology for applications such as smart watches, smart phones and AR or VR headsets where lower power consumption for the same brightness is desirable because it extends the time between battery charges. Moreover, the individual pixels in the display can be made smaller without compromising on brightness. This is desirable for applications such as smart watches and smart phones because it enables users to see the screen even in bright sunlight.

Further into the future, micro-LEDs may also be used miniaturised opto-electronic tweezers, optical cochlear implants, mask-free lithography and for multi-site neuron stimulation in brain/machine interfaces.

A high-growth market

According to a report published by Market Data Forecast in April 2021, the global micro-LED market is estimated to be worth US$2,588m in 2021 and to reach US$20,501m by 2026. This is equivalent to a CAGR of 51% over the forecast period.

Commercialisation status

Display manufacturers have launched micro-LED models

Exhibit 1: Video of micro-LED technology being deployed in large displays

Source: Sony

The technology appears on the cusp of commercialisation. In December 2019, Chinese display manufacturer **Konka (000016:CH)** launched large tiled micro-LED displays under the APHAEA brand. These modular displays were demonstrated in several possible configurations including 118" 4K retailing at around $240,000 and 236" 8K retailing at $1.25m. LG Electronics (part of **LG Corp 003550:KS**) launched its MAGNIT TV product in September 2020. MAGNIT TVs are made from eight modules, which are tiled to give a 163" display. Having introduced 'The Wall' micro-LED screens in 2019/2020, **Samsung Electronics (005930:KS)** announced at the 2021 Consumer Electronics Show (CES) that it was targeting the home consumer market with a range of micro-LED screens from 70" to 110", which would be available by the end of the year. Unlike 'The Wall', which had to be assembled on-site from smaller panels, these will ship as complete, single panels. **Sony (6758:TY0)** unveiled its micro-LED TV range at CES 2020. The range included 75", 88", 93" and 110" displays.

Demonstrations of micro-LEDs in displays for wearable applications

In December 2020, Konka demonstrated what MicroLED-info believes was the world's first micro-LED watch at the 2020 Chongqing Micro-LED Industry Innovation Forum. The watch used a 2" micro-LED display incorporating LED chips of 30µm. (A micrometre – µm – is one millionth of a metre.) Konka stated that the battery life of this watch was up to 35 days. It was not clear how close Konka was to commercialising this product. Shortly afterwards, micro-LED specialist PlayNitride, which DigiTimes notes is intending to list on the Taiwan Stock Exchange by the end of 2021, demonstrated its micro-LED technology in both TV sized displays and wearable displays at CES 2021. PlayNitride has a strategic alliance with display manufacturer **RiTDisplay (8104.TPE)** for wearable applications. Chinese LED epitaxy and chip manufacturer **Sanan Optoelectronics (600703:SS)** has formed a JV with China-based display producer China Star Optoelectronics Technology (CSOT), part of **TCL Technology Group (000100:SHE)**, to develop micro-LED materials and production processes and equipment. In 2019, CSOT demonstrated a 3.3" transparent micro-LED display, which was developed in collaboration with PlayNitride.

Supply chains are ramping up production

Sony is purchasing micro-LED chips from manufacturer of LED chips and wafers Epistar**,** which is part of **Ennostar (3714:TPE),** from PlayNitride and from Sanan. In April 2021, LEDinside noted that Epistar's mini-LED and micro-LED manufacturing joint venture with China-based LED display maker **Leyard Opto-Electronic (300296:SHE),** in which the partners have jointly invested $142m, commenced mass production in October 2020 and is expected to manufacture at full production in 2022. In March 2021, MicroLED-info announced that Sanan expected to commence trial production at its $1.78bn mini-LED and micro-LED production site later that month. PlayNitride started volume production at its first production line, which uses **Aixtron (AIXA:XETR**) equipment, in 2019, using the output to make sample quantities of its small wearable displays. It started construction of its second production line in September 2020. Konka is making its own micro-LEDs, also using Aixtron equipment.

M&A activity

Nanosys, which Bloomberg states is planning an IPO through a merger with **SPAC GigInternational1 (GIW:US**), is one of the world's largest suppliers of quantum dots (see the third report in this series for details). Its quantum dots are used by companies such as Samsung to improve the brightness and colour range of TV displays. In May 2021 Nanosys announced that it had acquired micro-LED firm glō. Prior to the acquisition, glō had invested over $200m in micro-LED epitaxy, device technology and its patented room temperature wafer transfer technology. The transaction expands Nanosys' technology portfolio to address a wider range of display applications including smaller displays for AR applications.

The science behind LEDs and micro-LEDs

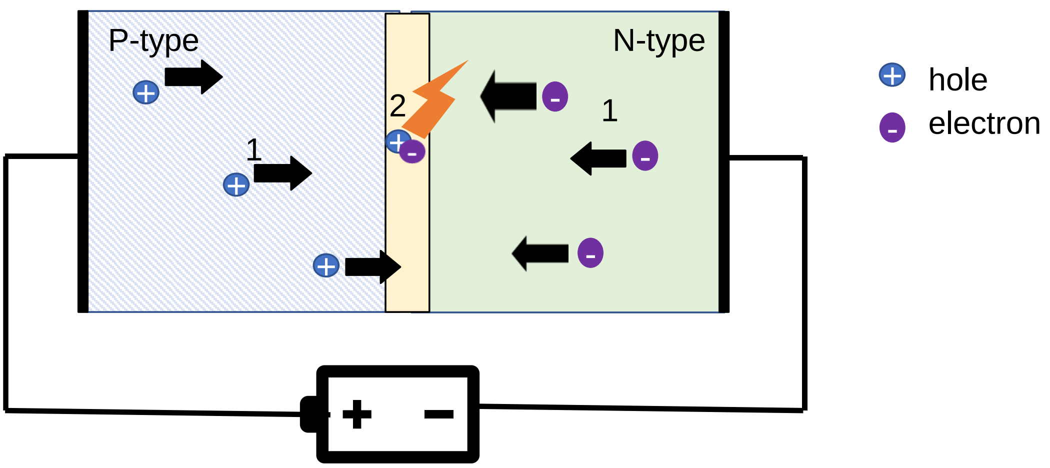
When is an LED actually a micro-LED?

Typically, an LED chip used for general lighting applications is larger than 200 µm × 200 µm so it can emit sufficient light. As the name suggests, micro-LEDs are smaller, around 20 µm × 20 µm. While normal size LEDs have become commoditised, significant challenges regarding the manufacture of micro-LEDs remain. This means that the market, which is potentially very large, is still in its infancy. It also means that there is potential for good returns for those companies that can solve these technical challenges.

How an LED works

An LED consists of two layers of semiconductor material, one known as 'n-type', which has been created to have extra electrons or negatively charged particles, the other known as 'p-type', which has been created so it has too few electrons, which is equivalent to containing positively charged particles referred to as 'holes' (see Exhibit 2). When an electric voltage is applied across the diode, the electrons are attracted to the positive anode and the holes to the negative anode (1). When an electron meets a hole (2), the hole is filled in, so neither the electron nor the hole exist anymore, but their energy is converted to tiny packet of light energy (2). If the electric current is turned off or reversed, the electrons and holes stop moving and no light is emitted.

Exhibit 2: LED structure



Source: Edison Investment Research

Changing the colour of an LED/micro-LED

The colour of light emitted depends on the amount of energy the electron and hole have, which depends on the structure of the semiconductor material. Different elements can be added to the semiconductor material in varying proportions to change the energy emitted when an electron and a hole recombine and thus the wavelength of the light emitted by the LED or micro-LED. The human eye interprets the different wavelengths as different colours. Red light has a wavelength of around 660nm. Blue light has a wavelength of around 450nm and is produced when electrons with more energy recombine. An LED emitting blue light typically uses gallium nitride (GaN) and indium gallium nitride (InGaN) layers deposited on a sapphire wafer. An LED emitting red light typically uses aluminium gallium indium phosphide (AlGaInP) on gallium arsenide (GaAs) material, though often 'red' LEDs start by emitting blue or green light, which is modified using phosphors or quantum dots to produce red light.

Solving micro-LED manufacturing challenges

Various technological solutions are being developed to cut the cost of manufacturing micro-LED displays, thus encouraging adoption. These include techniques for incorporating micro-LEDs into displays more efficiently and for reducing the cost of manufacturing the LEDs themselves. During an interview in October 2020, PlayNitride's CEO predicted that the production costs of micro-LED display technology would drop by as much as 95% in five years, making it competitive with OLED technology. There is also significant development work ongoing in improving the brightness of LEDs for wearable displays.

Manufacturing complete displays

The tiny size of micro-LEDs poses significant manufacturing challenges, which has held back technology deployment. Two different approaches are being developed to incorporate the individual micro-LEDs into displays.

Pick-and-place approach being adapted for larger displays

In the 'pick-and-place' approach, each individual micro-LED is picked up, precisely positioned onto the display backplane and electrically connected to the driver chip. This approach is currently used for larger displays. For a 4K display panel, this means placing almost 25 million LEDs, three for each pixel, to an accuracy of ±10µm. Doing this on an individual basis is not economic, so companies such as **Apple (AAPL:US)** owned company LuxVue, PlayNitride, US start-up Rohinni and Ireland based X-Celeprint, which is a wholly owned subsidiary of Belgian holding company Xtrion, are developing a variety of techniques for transferring multiple LEDs simultaneously.

The pick-and-place technique is particularly well suited to the manufacture of displays where the active LED area is only a small portion of the total. This potentially changes the competitive pricing versus LCD or OLED technology for applications such as video-walls, which do not need a high pixel density. Additionally, the space between pixels can be used for sensors or solar cells, creating the opportunity for new applications such as smart displays and displays that do not need external power sources.

Monolithic approach for small displays

Exhibit 3: Video of micro-LED display technology in smart glasses

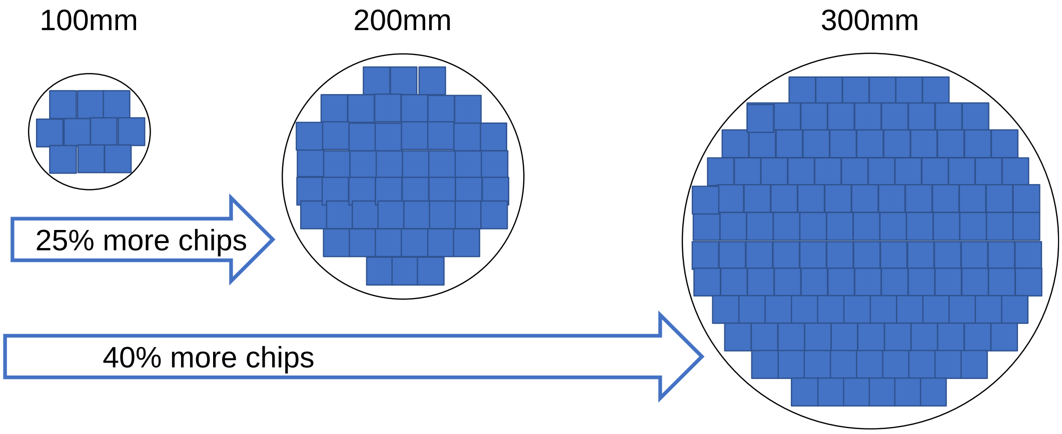
Source: Plessey Semiconductors

Plessey Semiconductors has developed an alternative 'monolithic' approach in which all of the micro-LEDs forming a small display are deposited together on a gallium nitride on silicon (GaN-on-Si) wafer using metal oxide chemical vapour deposition (MOCVD) equipment from Aixtron, with multiple arrays fitting onto one wafer. The wafer is cut up into individual arrays, each of which is mounted on a display backplane so that the bumps of conductive material 1 micron across connecting each pixel of the array to the corresponding driver match up correctly. The size of wafers that LEDs can be grown on (up to 300mm diameter) limits the monolithic approach to relatively small-size displays such as near-to-eye projectors and smart watches. However, the technique allows manufacturers to create arrays with pixels as small as 1µ, meaning that they can even be integrated into contact lenses.

Better economics from larger substrates

Another factor affecting the economics of adoption is the cost of manufacturing micro-LEDs. At present most LEDs use sapphire substrates. These are limited to 100mm and 150mm diameter while silicon wafers are usually 200mm or 300mm in diameter. German IP licencing company Allos Semiconductors has developed a technique for manufacturing GaN LEDs on 200mm and 300mm silicon wafers. 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 LED chip by 25% (see Exhibit 4). Moving from a 100mm wafer to a 300mm wafer potentially reduces the unit cost by 40%. Further cost reductions can also be realised because silicon wafers can be processed on conventional low-cost, high-yield silicon processing lines.

Exhibit 4: Increasing wafer diameter improves economics



Source: Edison Investment Research

Better economics from more uniform micro-LEDs

Typically, the wavelengths emitted by LEDs/micro-LEDs across a typical GaN-on-sapphire wafer vary so much that each LED chip needs to be tested and sorted into one of several 'bins' to ensure that each pixel emits the light in the correct wavelength range. This is a significant undertaking for a large 4K display formed from micro-LEDs and adds to the cost. Consequently, improving uniformity is very important for bringing down the cost of large micro-LED displays. Improving uniformity also reduces the need to remove faulty LEDs from a display once they have been transferred, further reducing costs. Wavelength uniformity is very dependent on precisely controlling the temperature of the wafer while the LEDs are being deposited and the flow of gases within the reaction chamber. Allos Semiconductor has worked with MOCVD equipment manufacturer **Veeco Instruments (VECO:US**) on its micro-LED process to give better wavelength uniformity across the wafer.

Improving red and green micro-LED brightness for smaller full colour displays

Most display applications are full colour and therefore need a red, a green and a blue element for each pixel. The most straightforward way of achieving this is for each pixel to contain three micro-LEDs, one of each colour. If these are to be formed from the same material family, this means using GaN for all three colours. However, GaN red and green LEDs are not as efficient at converting electricity to light as blue GaN LEDs. **Soitec (SOI:FP)** is addressing this by developing a substrate that improves the efficiency of the red and green LEDs. An alternative approach is to use three blue or UV LEDs with phosphors or quantum dots to convert the blue LED to red and green or the UV LED to blue, red or green. (Quantum dots will be covered in a future note in this series.) Phosphors are already widely used with white LEDs in general lighting. However, the size of a phosphor particle is 30µm, making it impossible to shrink pixels beyond this size and also leading to low colour uniformity for larger pixels. Quantum dots are smaller than phosphors and can be tuned to specific wavelengths by changing their size. This potentially gives better colour uniformity and reduces the smallest practical pixel size to 4µm. Plessey Semiconductors sees this as a route for achieving smaller, higher-resolution micro-LED displays.

Equipment manufacturers involved in micro-LEDs

MOCVD equipment deposits LEDs quickly

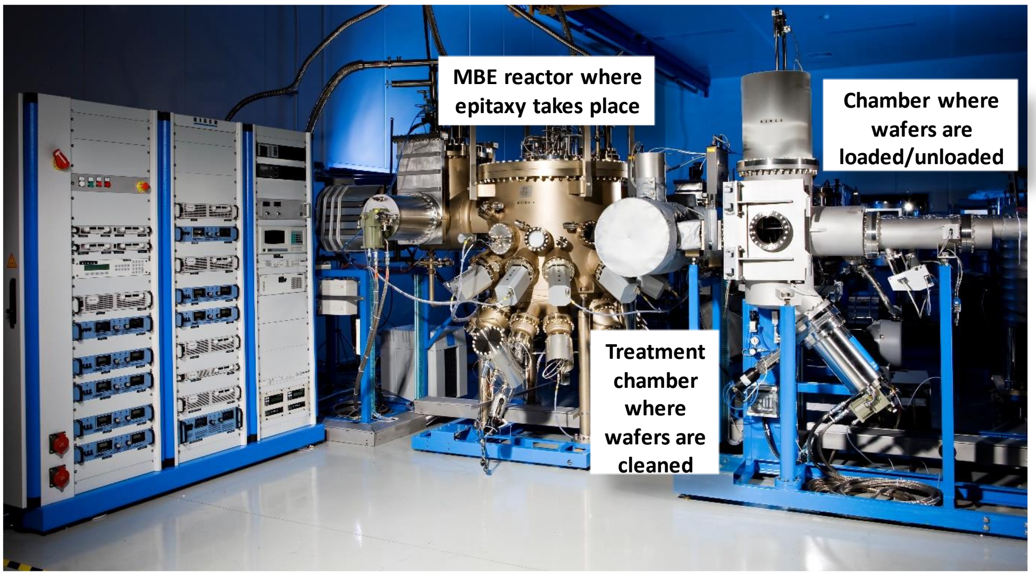
Conventional LEDs are manufactured using MOCVD equipment from **Advanced Micro-Fabrication Equipment (688012.SS)**, Aixtron or Veeco. In this technique, an organometallic compound containing gallium and ammonia, which is a combination of nitrogen and hydrogen atoms, are injected into a chamber containing the substrate. The two gases react when they reach the heated substrate to form GaN. The substrate needs to be heated to at least 940°C to crack the ammonia into nitrogen atoms, which form the nitride in GaN, and hydrogen atoms. At lower temperatures than this, insufficient amounts of ammonia split to create nitrogen atoms, giving defects in the crystal structure where nitrogen atoms ought to be.

High MOCVD temperatures unsuitable for red and green micro-LEDs

The high temperature needed for MOCVD causes some of the indium dopants in the active area (where the electrons and holes recombine) to diffuse both out of and within the active layer, creating areas that are brighter than others. This effect impairs the uniformity of both conventional and micro-LEDs, although it is more serious for micro-LEDs. Moreover, in theory, it should be possible to manufacture blue, green and red LEDs on the same GaN wafer by introducing high levels of indium dopant in the areas that will form green LEDs and even higher levels of indium dopant to the areas that will form red LEDs. However the high temperatures required in the MOCVD process make it very difficult to create green and red LEDs in this way because the dopants migrate when the structure is heated.

Riber and BluGlass offer alternative technologies

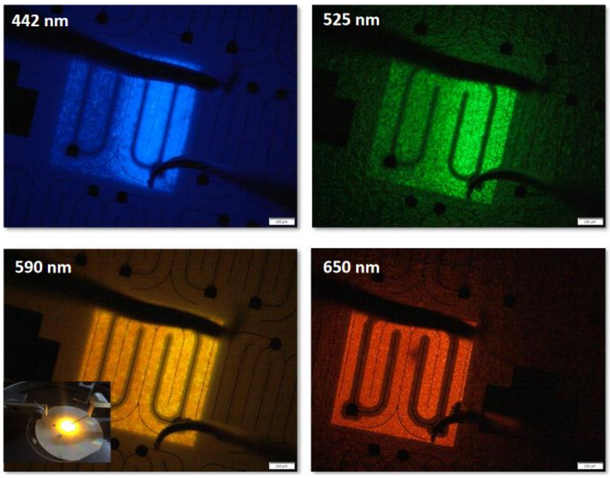
Exhibit 5: Riber MBE equipment



Source: Riber

Established equipment manufacturer **Riber (ALRIB: EPA)** (see Edison research on Riber) offers an alternative technology, molecular beam epitaxy (MBE) for making the compound semiconductor materials used for micro-LEDs. MBE uses pure metal sources for the gallium and splits up nitrogen gas using a strong electric field to create a plasma formed of active nitrogen. It therefore operates at a substantially lower temperature than MOCVD, so does not have the problems that MOCVD does when manufacturing micro-LEDs. Riber is working with the Centre de Recherches sur l'HétéroEpitaxie et ses Applications (CRHEA), part of the Université Côte d'Azur, on the fabrication of red and green coloured micro-LEDs with the highly doped active layers processed using MBE, the others using MOCVD.

Exhibit 6: Red/green/blue LEDs grown using BluGlass's RPCVD technology



Source: BluGlass

Australian technology company **BluGlass** (**BLG:ASX)** has developed a novel technique known as remote plasma chemical vapour deposition (RPCVD), which can be used in conjunction with MOCVD technology to deposit critical layers such as the active layer in a micro-LED wafer (see Edison research on BluGlass. Like MOCVD, RPCVD uses an organo-metallic compound as the gallium source but, unlike MOCVD and like MBE, it splits up nitrogen gas into plasma. Creating active nitrogen in this way means that RPCVD operates at a significantly lower temperature than MOCVD. BluGlass has demonstrated good progress in manufacturing epitaxy for orange and red LEDs and micro-LEDs using its patented RPCVD technology (see Exhibit 6).

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