Assessment of BluGlass' RPCVD technology

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Executive Summary

The increasing use of LEDs is visible all around us. Alongside general lighting, LEDs can be found in advanced technologies such as high-definition displays (e.g. TVs, Laptops, mobile phones, watches etc..), AR and VR headsets, cameras, and communications. Market demand is clear, given the market figures for packaged LED general lighting ($6.8B in 2018), and MicroLED (forecast to reach $20B by 2024). As the LED market continues to grow, consumers are demanding lower cost, high performance devices. Commercially available high performance, LEDs are based on a material called Gallium Nitride (GaN). GaN LEDs are manufactured using an expensive, high temperature technique called Metal Organic Chemical Vapour Deposition (MOCVD).

Australian cleantech company, BluGlass Limited (BLG), have developed an alternative, lower cost deposition technique. BluGlass are developing new equipment and new material processes based on their patented Remote Plasma Chemical Vapour Deposition (RPCVD) technology. This technology can be used to produce GaN based material for the LED market. Furthermore, RPCVD processes can also be applied in the fabrication of GaN Laser Diode market, estimated to be valued at US$14B in 2019.

This purpose of this report is to provide accessible technical information regarding BluGlass' innovative RPCVD technology (Section 1), and explore its advantages over existing MOCVD manufacturing methods (Section 2). Some of the benefits of RPCVD over MOCVD include lower temperature processes, higher performance devices (target greater than 10% increasing light output), and significantly lower input costs. The key benefit of RPCVD is that it can be used alongside mature MOCVD manufacturing techniques, which enables the advantages of both methods to be exploited (Section 3).

BluGlass' key assets can be grouped into RPCVD hardware and RPCVD processes. BluGlass have demonstrated their RPCVD hardware in an operational environment. They are currently optimising their hardware design (Section 3.1.1) and are also collaborating with a leading global equipment manufacturer (Aixtron), on a retrofit project to upscale manufacturing capabilities. The results of this work are very important, since there is clear potential for licencing of RPCVD hardware designs.

BluGlass has specialist expertise in low temperature RPCVD GaN deposition. A key advantage of RPCVD is that the GaN layers are 'activated as grown'. This means further thermal processing steps are not required, which gives RPCVD another advantage over MOCVD (more flexibility to deposit multiple layers) (Section 3.1.2).

BluGlass' RPCVD Tunnel Junction process (Section 4.2) is of particular interest since this can unlock new opportunities in high performance single and cascade LEDs (Section 4.3) and laser diodes (Section 4.5). Since BluGlass have already established many of the processes needed to form a Laser Diode through their extensive LED work, they expect to rapid progress towards a market ready product. Initial results from the first prototypes will provide some clarity regarding the probability of rapid progress.

BluGlass' are planning to commercialise their RPCVD hardware designs, targeting the global MOCVD equipment market which is forecast to be worth $1.4B by 2025. RPCVD GaN processes for LED applications (Single TJ, Cascade and MicroLED) will be commercialised through licencing, foundry service (EpiBlu) or joint venture/Joint development agreements. Technology roadmaps are outlined for each target process application (Section 4) and the status of the BluGlass' commercialisation activity is outlined in Section 5.

It is interesting to note that BluGlass do not plan to licence RPCVD GaN processes for Laser Diodes, since they can work with suppliers and have the capacity to manufacture and supply this relatively low volume, high value product.

In summary this report

- presents a clear analysis of the benefits of BluGlass' key technologies/IP assets
- presents a benefit comparison of RPCVD, relative to the incumbent MOCVD technology (advantages and disadvantages) for each of the identified applications
- identifies potential barriers to commercialisation
- identifies key LED and Laser Diode players
- provides an assessment of the deliverability/manufacturability of the technology:
    - Summarising current status
    - Identifies what is needed for effective deployment into the end markets

About BluGlass

BluGlass Limited (BLG) is an Australian based clean technology company. BluGlass are exploiting their patented Remote Plasma Chemical Vapour Deposition (RPCVD) technology as a breakthrough alternative for the manufacture gallium nitride (GaN) semiconductor materials. They are focussed on the development of new equipment and new material processes, which are used to manufacture GaN nitride semiconductor devices such as, high efficiency LEDs and Laser Diodes.

1. What is RPCVD?

Remote Plasma Enhanced Chemical Vapour Deposition (RPCVD) is a low temperature technique, which is used to deposit material on semiconductor substrates. RPCVD uses a plasma to enhance the reaction rate of the gases used in the process. The process is described as remote, since the substrate is not in direct contact with plasma during the deposition.

BluGlass develop RPCVD equipment and RPCVD processes for the deposition of Gallium Nitride (GaN) based materials for LED and Laser Diode devices. It is important to note that the deposition of GaN based materials using RPCVD is a **new application** of an **established deposition technique**.

A photograph of a BluGlass' RPCVD tool and a schematic cross section of the RPCVD chamber are depicted below (Figure 1).

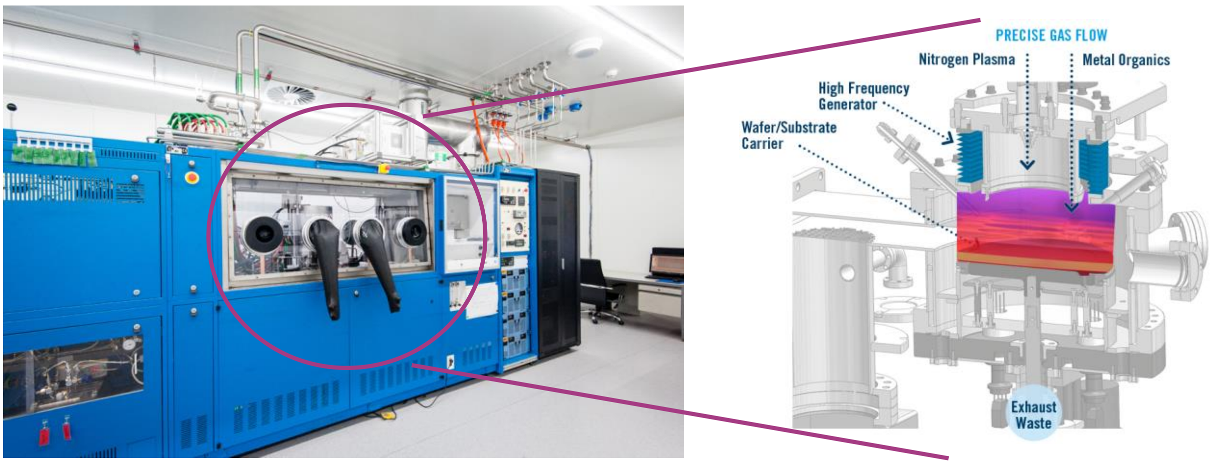


Figure 1: RPCVD Hardware Left: BluGlass' retrofitted Thomas Swan 19x2 inch MOCVD system (BLG-300II). Right: A schematic showing one of the RPCVD designs

2. GaN Based Materials for LEDs and Laser Diodes

Industrial GaN based materials for LED and Laser Diode devices are usually deposited using another technique called Metal Organic Chemical Vapour Deposition (MOCVD). MOCVD is a high temperature growth process that uses metal organic* sources.

MOCVD is used to deposit a number of layers of GaN based material. These layers are subsequently manufactured into LED and Laser Diode devices Figure 2.

How LEDs are made and the value chain

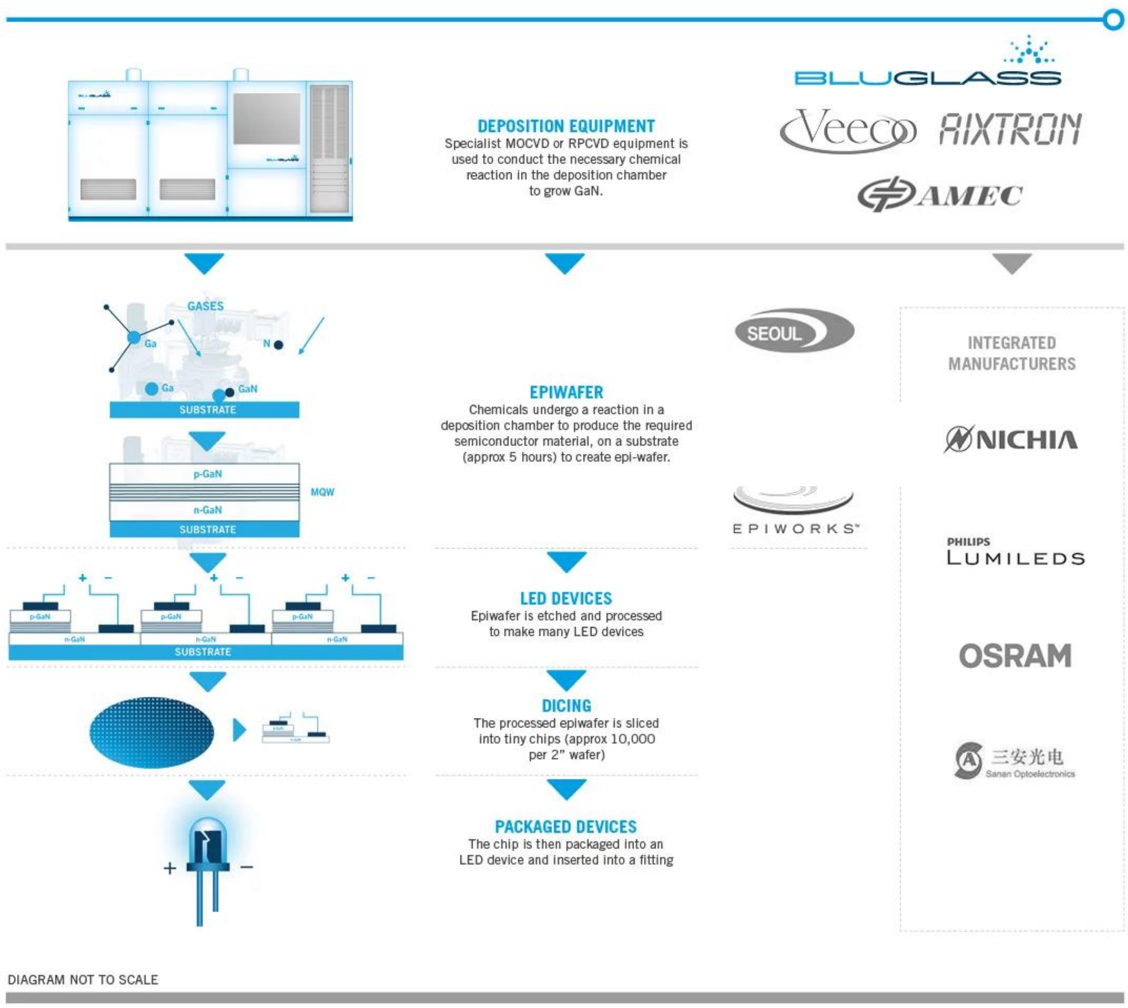


Figure 2: How LEDs are made and the value chain

MOCVD is a very well established, robust processing technology, which boasts excellent uniformity, repeatability and very good device performance. However, GaN MOCVD is a very high temperature process that uses hydrogen-rich ammonia. This limits the scope of its use in multi-layer growth, since the carefully controlled properties of the initial layers can be adversely affected by the high temperature growth and high levels of hydrogen used to grow subsequent layers (Figure 4). This, in turn, leads to a reduction in device performance.

* Class of chemical compound

RPCVD can provide more flexibility for multi-layer GaN growth since:

1) It is a lower temperature deposition technique
2) RPCVD GaN process uses inert nitrogen, rather than highly toxic, hydrogen rich ammonia (NH_3).

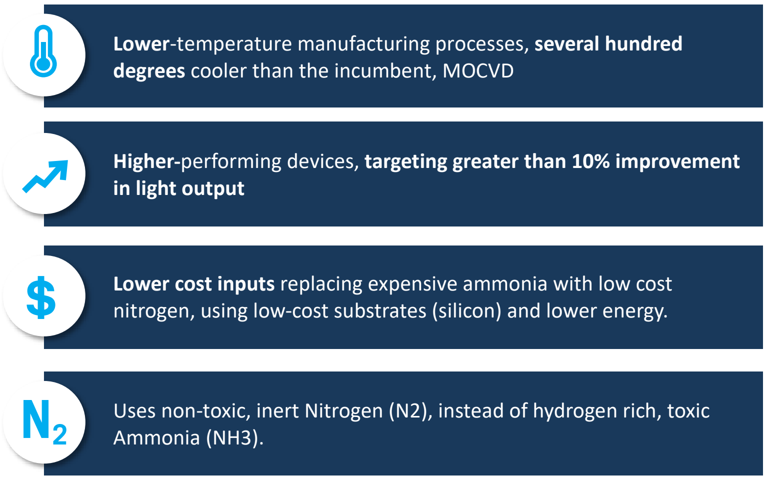


Figure 3: Advantages of RPCVD technology for the deposition of GaN based materials

These unique properties have the potential to unlock a significant improvement in LED and Laser Diode device performance.

Figure 3 highlights some of the advantages of RPCVD technology for the deposition of GaN based materials.

3. MOCVD and RPCVD – Complementary Techniques

A key advantage of BluGlass' RPCVD equipment, is that it can be implemented alongside MOCVD, and can be retrofitted on manufacturing scale MOCVD reactors. BluGlass aim to exploit the advantages of mature MOCVD technology, whilst addressing some of the limitations using their proprietary RPCVD technology. The following section summarises BluGlass' Expertise and key IP Assets.

3.1. BluGlass Expertise and IP Assets

BluGlass' knowledge and expertise can be categorised under RPCVD equipment and RPCVD process.

BluGlass specialist capabilities include:

- Hardware (design and implementation and testing)
- Process (design and testing).

3.1.1. Current Status of BluGlass Key IP Assets in RPCVD Hardware Design

- Two RPCVD platforms (BLG-300 and BLG300II) developed using commercially available MOCVD tools

- Volume manufacturing scale MOCVD equipment (AIX2800 G4) retrofitted with RPCVD capabilities

Table 1 below provides an overview of the current status of BluGlass' RPCVD Hardware.

BluGlass Equipment Name	**Original Tool**	**Capacity & Wafer size (")**	**Current RPCVD Hardware Status**
BLG300 (Design B)	Thomas Swan (Aixtron)	19 x 2" 5 x 4"	BLG300 has been demonstrated in an operational environment without significant modification for a number of years. This tool is used to carry out process development and collaborative work with customers. The reactor chamber top plate design has been optimised from design 'A' to design 'B', to improve uniformity beyond 4" wafers. Note that for Laser Diode development and production on 2" wafers, this system is deemed sufficient with respect to uniformity. However, the system is not yet in its final form as some further improvements are needed, which will require design modifications. In summary, this tool can be considered as a commercially usable prototype system.
BLG300II	Thomas Swan (Aixtron)	19 x 2" 5 x 4" 1x 6" 1 x 8"	This tool has been online since July 2019 and can accommodate multiple reactor top plate designs. BluGlass credibly expect performance improvements (surpassing BLG300) but there are still a number of unknowns with the most recent top plate design. Although this prototype tool has been demonstrated in relevant environment, further development work is needed to upgrade this to a commercially usable prototype system for 6 and 8" wafers.
BLG-G4	Aixtron AIX2800 G4	42 x 2" 11 x 4" 6 x 6"	BluGlass is collaborating with the equipment manufacturer Aixtron. Following 9 months of design, component test, building, and completing the assembly, they are on track commission this tool mid-2020. The retrofit of a large-scale, commercial Aixtron MOCVD reactor with RPCVD is significantly different to BluGlass' previous retrofit activities, so it is deemed to be at an earlier stage of development. There is potential for unknown challenges and thus this deemed to be high risk, early stage R&D. The quality of the first depositions will be critical to determine the risk status. For example, the first attempt at retrofit may not meet performance expectations. However, if initial retrofit performs well, the system could potentially quickly progress towards commercialisation.

Table 1: Overview of the current status of BluGlass' RPCVD Hardware

BluGlass' BLG300 and BLG300II RPCVD tools are considered to be at the experimental development stage (commercially usable prototypes), but are not yet ready for commercialisation of large wafers. The most recent reactor top plate design still needs to be validated and performance successfully demonstrated on 6" and 8" wafers. It should be noted that for LED manufacturers (GaN on sapphire) 4" and 6" wafer sizes are sufficient whereas GaN on Silicon related applications, wafers of 6" and larger are required. Industry is considering MicroLED applications with both GaN on sapphire and GaN on Silicon based implementations, so having RPCVD with the flexibility of wafer size is a critical interest to BluGlass.

The retrofit of a full commercial scale Aixtron MOCVD reactor (AIX2800G4) with RPCVD is deemed to be at an earlier 'industrial research' stage. This research activity is being carried out in collaboration with Aixtron (global leader in MOCVD equipment) and is of great commercial interest (See Section 5). Aixtron's commitment to this collaboration demonstrates a serious interest in the technology. Their engagement with BluGlass brings reassurance that they have confidence in the potential of this GaN based RPCVD technology.

Successful demonstration of RPCVD retrofit on production scale equipment will generate customer demand. However, commissioning activity (starting mid CY2020) is still in its infancy. Although rapid progression is not impossible, progression from early stage research to market ready would typically involve several development iterations, managed within a programme of activities implemented over a period of 2 or 4 years. However, it is worth noting that BluGlass demonstrated rapid progress with the development of BLG300. This, coupled with their collaboration with Aixtron, brings confidence that this activity can be expedited. Furthermore, Aixtron may want to license the technology at an earlier stage, and complete the final stages of development themselves.

BluGlass have identified the following commercialisation routes for their RPCVD hardware.

- Licensing Equipment Design - Retrofitting MOCVD kit to include RPCVD capability
- Joint Venture/Joint Development Agreements (contract R&D, Hardware Prototyping etc..)

These commercialisation routes will be further explored in Section 5.

3.1.2. Current Status of BluGlass Key IP Assets in RPCVD Process

- Low temperature GaN growth
- Low temperature RPCVD Tunnel Junction

RPCVD GaN growth processes have applications in Single LED, Cascade LED and Laser diode.

The properties of the GaN layers are controlled by 'doping' (adding other species) the layer making them positive (p-type) or negative (n-type). Magnesium (Mg) is often added to GaN to make the layer p-type. However, not all of the Mg added to the layer will contribute to the device performance, only 'active' Mg will influence device performance. In MOCVD growth, the level of active Mg in GaN is usually controlled by further high temperature process steps ('thermal activation') Figure 4(a).

In the case of multilayer MOCVD GaN based structures, the hydrogen rich atmosphere and the high temperature conditions of subsequent MOCVD GaN layer deposition reduces the amount of active Mg (i.e. passivating the p-GaN). This leads to a reduction in device performance. This inherent limitation of MOCVD growth is illustrated in Figure 4 (b) below.

A key advantage of RPCVD is that p-GaN is 'activated as grown'.
This means the amount of active Mg can be controlled as grown, and does not need further process steps (see Figure 4 (c))

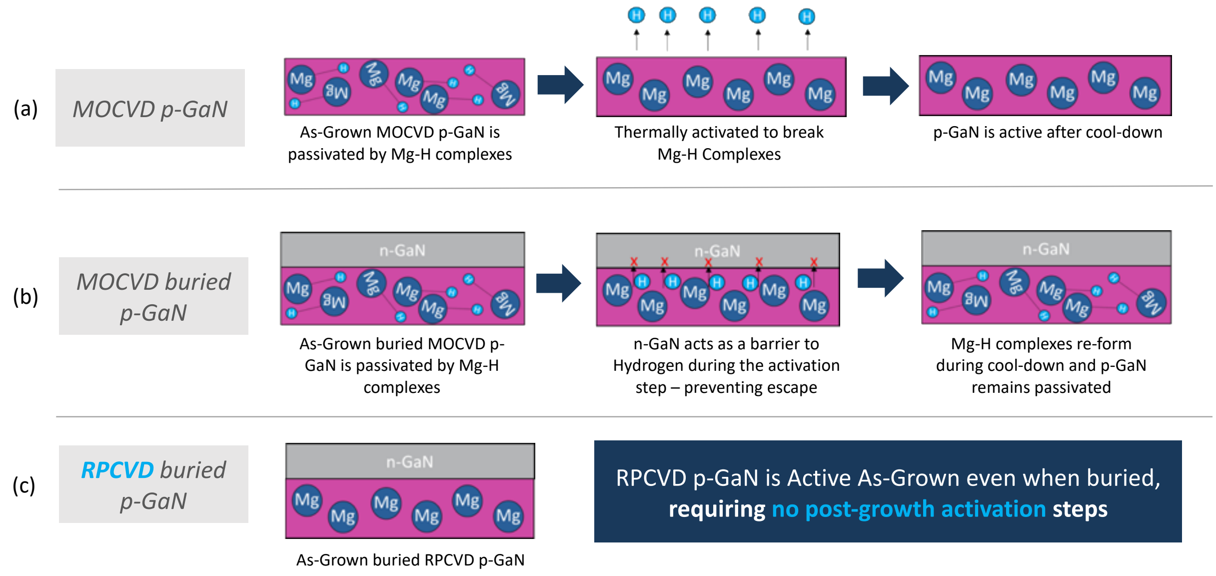


Figure 4 Activation of Magnesium Doping in MOCVD and RPCVD GaN

A Tunnel Junction (TJ) is a junction of p type and n type layers (p-n junction) that has very high doping levels either side of the junction (p^{++}/n^{++}). RPCVD enables high 'active as grown' doping capability for both p^{++} GaN and n^{++} GaN. RPCVD also enables a sharp Mg dopant profile at tunnel junction interface, which is very difficult to achieve with MOCVD. Further information on TJ are given in Section 4.3 (Cascade LEDs).

BluGlass have identified the following commercialisation routes for RPCVD Process.

- Licensing – MOCVD/RPCVD process and LED based device IP
- Foundry - RPCVD foundry (epitaxial wafer growth and characterisation services to meet individual customer needs – Trading as EpiBlu)
- New GaN based Product - BluGlass will produce Laser Diodes. They will cover the whole Laser Diode Manufacturing process using suppliers and process partners.
- Joint Venture/Joint Development Agreements (contract R&D, Prototyping etc..)

These commercialisation routes will be further explored in Section 5.

In the following section we will explore BluGlass' target GaN based device applications.

4. BluGlass' Target Applications

BluGlass' RPCVD growth processes can be tailored for application in several GaN based device technologies. In fact, in the semiconductor sector it is standard procedure to transfer knowledge and processes between similar device architectures. BluGlass are applying their RPCVD growth process to develop GaN LEDs (single, cascade and Micro) and Laser Diodes.

For each application, we will:

- Compare figures of merit for standard GaN devices and BluGlass' RPCVD GaN device architectures.
- Summarise barriers to commercialisation
- Present technology roadmaps

4.1. Single LEDs

GaN LEDs consist of a number of layers of GaN based materials that are usually manufactured using MOCVD (Fig 5). The properties of the light emitting 'Multi Quantum Well' layer of the device is critical for light output performance. The MQW layer contains Indium, which is sensitive to temperature. When the top layers of GaN are grown by high temperature MOCVD, this causes Indium to diffuse out of the MQW layer, which lowers the output of light. This issue is worse for longer wavelengths (green/yellow) which need high concentrations of Indium in the MQW.

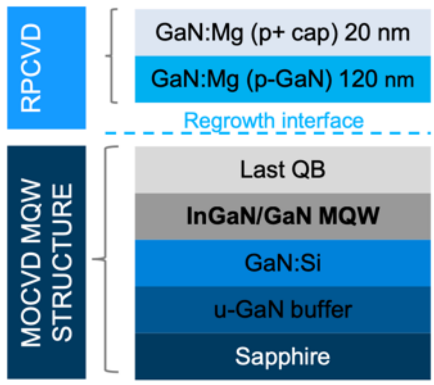


Figure 5 Schematic of BluGlass Single LED layers structure gown using a combination of MOCVD and RPCVD.

Indium diffusion from the MQW can be reduced by using low temperature RPCVD to grow the top layer of p-GaN. This method has significant potential to improve device performance in long wavelength LEDs. BluGlass have demonstrated an improved performance, proof of concept single LED device, using MOCVD to grow partial LED structure, and low temperature RPCVD to form the top p-GaN layer.

4.2. Single Tunnel Junction (TJ) LEDs

Conventional MOCVD LEDs use a partially transparent conducting oxide (Indium Tin Oxide – ITO) to spread the electrical current laterally across the top of the device. This generates light uniformly across the entire chip.

However, the ITO layer partially absorbs some of the light, preventing it from being released from the device. This results in lower LED efficiencies. The ITO layer can be replaced with a tunnel junction (TJ) and a low resistance top-n-GaN contact layer. The n-GaN contact layer will uniformly spread the current but with lower optical absorption compared to ITO. This will lead to increased light extraction and improved device efficiency.

Packaged Single TJ Blue LEDs (As at BluGlass AGM, November 2019)			
Figure of Merit	Standard	Key target	Performance to date
Light Output	592 mW	616 mW (4%)	618 mW
Forward Voltage (Vf)	3.4 V	3.4 V	4.1 V
Wall Plug (or Radiant) Efficiency	50%	54%	44%

The performance of BluGlass' single TJ blue LED to date is encouraging in terms of light output. However, further process development is required to optimise growth conditions to maintain this high light output, whilst reducing forward voltage, and increasing wall plug efficiency.

Further process development is required to achieve performance, uniformity and reliability targets, which will bring the growth process closer to commercialisation (license-ready).
The trigger for licensing is difficult to predict since as it can be based on a minimum performance specification of a prototype wafer. Further process improvement is then achieved by the licensee.

This performance specification trigger level may in fact be lower than the key target shown in the table, and will depend on the expectations of the customer. The key uncertainty here is that the time required to reach this trigger level is unknown and difficult to predict.

4.2.1. BluGlass Roadmap TJ LEDs

BluGlass are currently engaged with LED manufacturers (including Luminus) in initial technology demonstration/collaborations to replace the ITO to improve single LEDs performance and to realise cascade LEDs (Section 4.3) for high volume LED applications. Figure 6 presents BluGlass' roadmap for TJ LED products (Single TJ and Cascade LEDs).

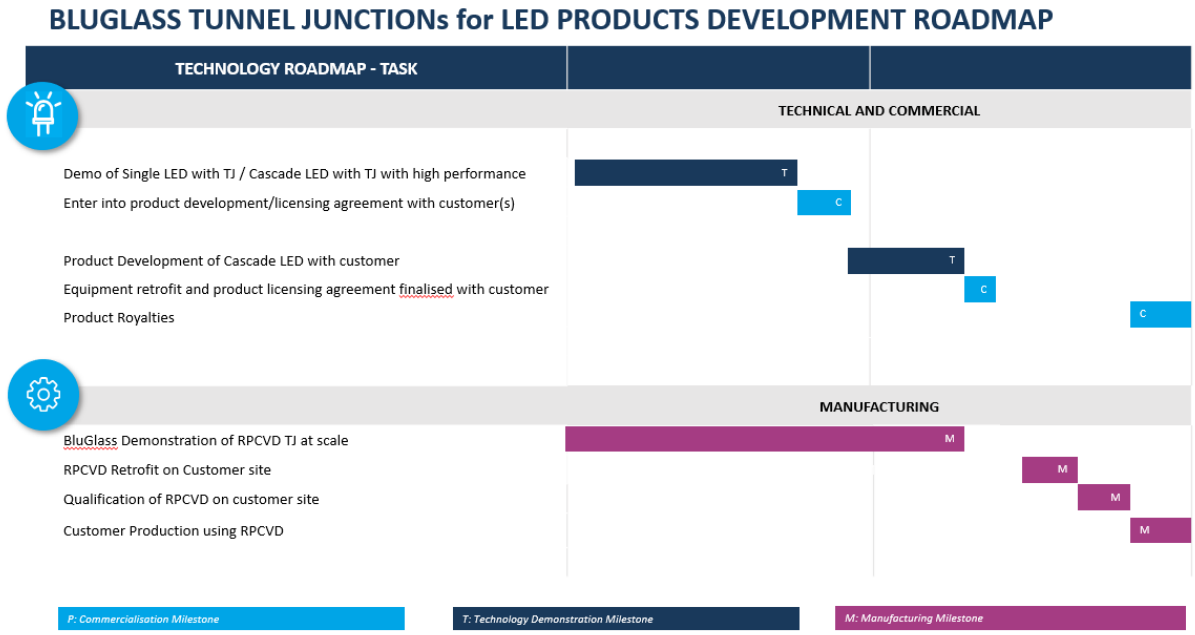


Figure 6: BluGlass Product Development Roadmap for TJ LED Products: Single and Cascade LED

Potential Technical Barriers to commercialisation	**Action**
Added tunnel junction must not increase device voltage	To mitigate the tunnel junction impact to device voltage incorporate an InGaN single quantum well (SQW) within the TJ so as to reduce the TJ resistance. However, the presence of the InGaN may lead to increased light absorption.

4.3. Cascade LEDs

Current GaN LEDs do not operate at their peak efficiency because of an issue known as 'Efficiency droop'. This is where the efficiency of the LED drops off significantly, when driven by a high current. When GaN LEDs are used in high brightness applications they require high driving currents, which results in the LEDs operating outside their peak efficiency regime. Poor efficiency results in devices giving out excessive heat. This has limited the use of LEDs in large, high brightness, high power applications.

High brightness can be achieved by arranging multiple LEDs, side by side, in an array.
This allows the desired brightness to be achieved, while maintaining sufficiently low driving current through each LED so that each LED is operating at peak efficiency. However, this solution increases the cost of manufacture. Furthermore, this solution is not acceptable in areas where the size of the device (footprint) is limited.

High brightness can be achieved by stacking two or more LEDs on top of each other (cascade LEDs), during the layer growth process. Cascade LED devices are grown vertically, so the footprint of the single chip device is much smaller. In summary, Cascade LEDs improve efficiency, reduce heat and enable the use of LEDs in large, high power applications.

Cascade LEDs require a critical device, a Tunnel Junction (TJ), to interconnect each LED in the vertical stack. However, the deposition of this TJ structure poses several challenges in conventional MOCVD processes, owing to the large amounts of ammonia used. BluGlass has developed an ammonia-free RPCVD TJ deposition process that can enable the manufacture of cascade LEDs and address the efficiency droop problem in high brightness LED applications.

BluGlass have demonstrated working Cascade LEDs, which has gained the interest of the key industry players (Bridgelux, Luminus – see Section 5).

As expected at this relatively early stage of development, the performance of the Cascade LEDs is not yet close to a full commercial specification. Significant further process development is required to optimise growth conditions to reduce forward voltage, increase light output and increase efficiency.

BluGlass has made progress on the initial proof of concept showing light output of the cascade LED structure as shown in Figure 7, a cascade LED structure wafer (not processed into a chip) with a green LED on top of a blue LED. Note that at this stage, the LEDs are contacted separately (2 separate spots on the wafer) so as just the top or the bottom LED lights up.

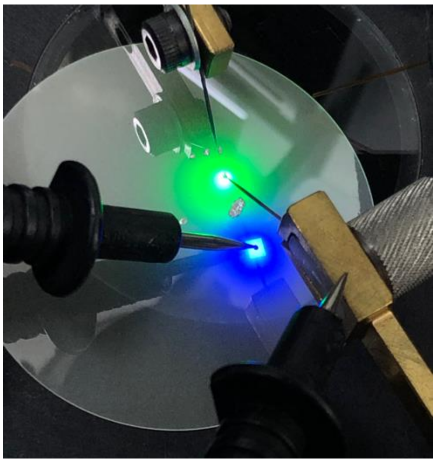


Figure 7: RPCVD green LED and RPCVD TJ grown on an MOCVD blue LED

Once the wafer material is processed (through a fabrication supplier) into a cascade device, it will possible to measure both LEDs at the same time. Working at the same time at the same spot. At the time of writing, these samples are awaiting fabrication in China.

Further development is required to achieve sufficient performance, uniformity and reliability targets required to bring the growth process closer to being ready to license. Again, the performance specification needed to successfully license the process, may be lower than the key target of a 10% improvement in efficiency and will depend on the expectations of the interested customers. The duration of the development work needed to reach this trigger level is unknown and difficult to predict.

4.3.1. Cascade LED BluGlass Roadmap

BluGlass are currently engaged in two separate collaborations (Bridgelux and Luminus) to demonstrate a high brightness cascade LED for general lighting and projection applications. As their results improve, BluGlass expect further LED manufacturers to trial RPCVD TJ technology.

See Figure 6, Section 2.2.1 for BluGlass' Product Development Roadmap for TJ LED Products: Single and Cascade LED.

Potential Technical Barriers to commercialisation	**Action**
TJ resistivity too high, so voltage of the cascade LED > 2x the single LED	Incorporate an InGaN single quantum well (SQW) within the TJ so as to reduce the TJ resistance, however the presence of the InGaN may lead to increased light absorption.
Growth of the TJ and upper LED damages the lower LED	Use combination of low growth temperature RPCVD and conventional MOCVD to limit the thermal exposure during the deposition of the TJ and upper LED
Upper LED performance not as good as lower LED performance due to challenges in growing on top of lower LED (a more complex structure with potentially rougher starting surface)	If required – enter into MOCVD development partnership with the MOCVD based LED manufacturer.

Other Potential Barriers to commercialisation	**Action**
RPCVD uniformity and scalability to larger wafers	Latest BLG-300II and commercial scale AIX 2800 G4 RPCVD chamber designs can be used for TJs and cascade LEDs

4.4. MicroLEDs

Microscopic LEDS (MicroLEDs) are arranged in an array to form MicroLED displays. Each MicroLED is an individual pixel of the display. This is an emerging technology. GaN MicroLED boast greater efficiency, improved brightness, and lower power consumption. BluGlass are working on MicroLED demonstration of RPCVD p-GaN in customer prototypes (X-Display, & others) and longer-wavelength multi quantum well (MQW) MicroLEDs such as green and red.

Blue and Green GaN-based MicroLEDs are currently achievable using MOCVD. However, GaN-based red LEDs are not currently available. Current MicroLED displays utilise a different material system (AlGaInP/GaAs) to produce the red LED. From a performance and manufacturing perspective, it is highly desirable to produce all three colours (RGB) for a MicroLED display out of the same material system. Hence, there is great interest in developing a red GaN-based LED.

A key challenge in achieving a red GaN based LED, is in the growth of good quality Indium-rich InGaN layers that produce the active region of the device (where the light is generated). Whilst very low growth temperatures are required to incorporate the large amounts of indium, the MOCVD process favours higher growth temperatures to achieve the best quality material.

Furthermore, the difference in the atomic spacing of the Indium-rich InGaN layers compared to the other GaN-based layers in a red LED, leads to significant strain within the device. This results in a reduction in efficiency. Finally, the top p-GaN layers of a red LED must be grown at sufficiently low temperatures to prevent thermal damage of the indium-rich InGaN layers beneath, which presents a significant challenge for MOCVD.

As described in section 3.1.2, low temperature RPCVD can be used to grow the top p-GaN layers preventing thermal damage of the InGaN layers below.

Blue and Green MicroLED devices using RPCVD p-GaN have been demonstrated in customer prototype MicroLED displays (Figure 8).

There is strong interest (from other existing BluGlass customers) in the use of RPCVD to grow the In-rich layers for long wavelength LEDs (green, yellow, amber and red) due to the lower growth temperature.

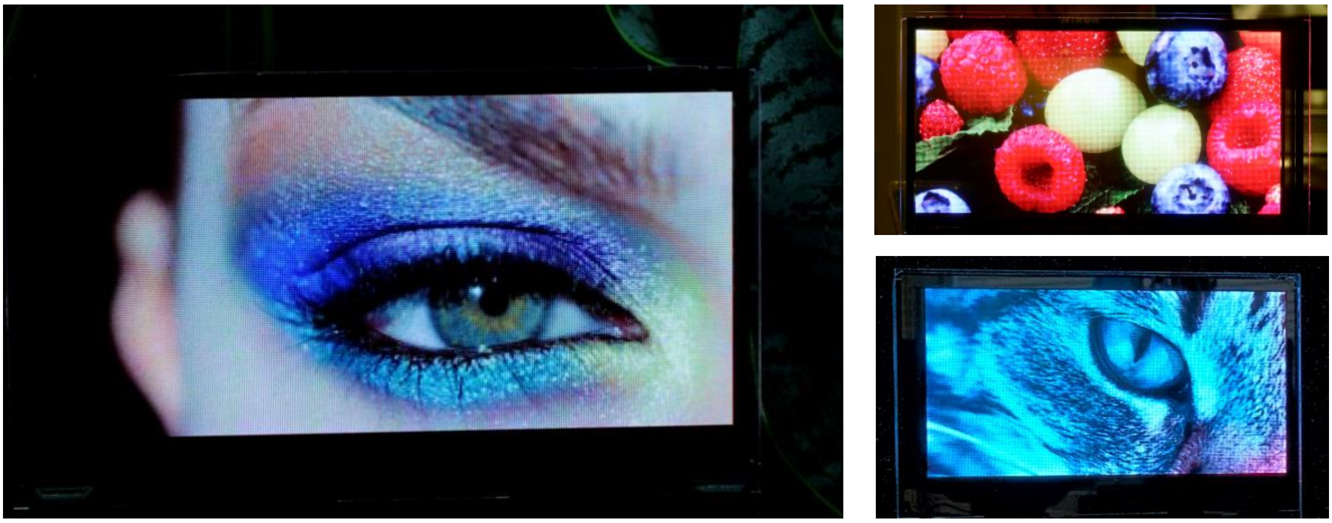


Figure 8 BluGlass foundry customer, X-Display (formerly X-Celeprint) MicroLED display prototypes grown using BluGlass' RPCVD technology

BluGlass have also demonstrated a working proof of concept Red MicroLED, which has captured the attention of potential customers (large global organisations). However, since BluGlass' Red GaN MicroLED is early stage R&D, significant development work is required to increase performance levels before prototype device can be demonstrated. Again, the time required to deliver this development work unknown.

Red Micro LEDs			
Figure of Merit	Standard	Key target	BluGlass Performance to date
External Quantum Efficiency (EQE) %	2.9% [1.1mW at 20mA at 618nm - Toshiba with MOCVD]	>15%	Working proof of concept demonstrated with ongoing development towards target

4.4.1. BluGlass Red MicroLED Roadmap

BluGlass have commenced work on Red MicroLED but this work is deemed to be early stage R&D. As a result, the predicted timeline for this work is not yet clear. Red MicroLED research is of particular interest to key players in the field, such as the major LED players and some other big names including Apple, Google, Facebook and Samsung, since there is low confidence that MOCVD will be capable of delivering a MicroLED solution.

BluGlass are seeking collaboration partners to fund additional activities in this area. BluGlass will seek to license the technology upon proof of concept.

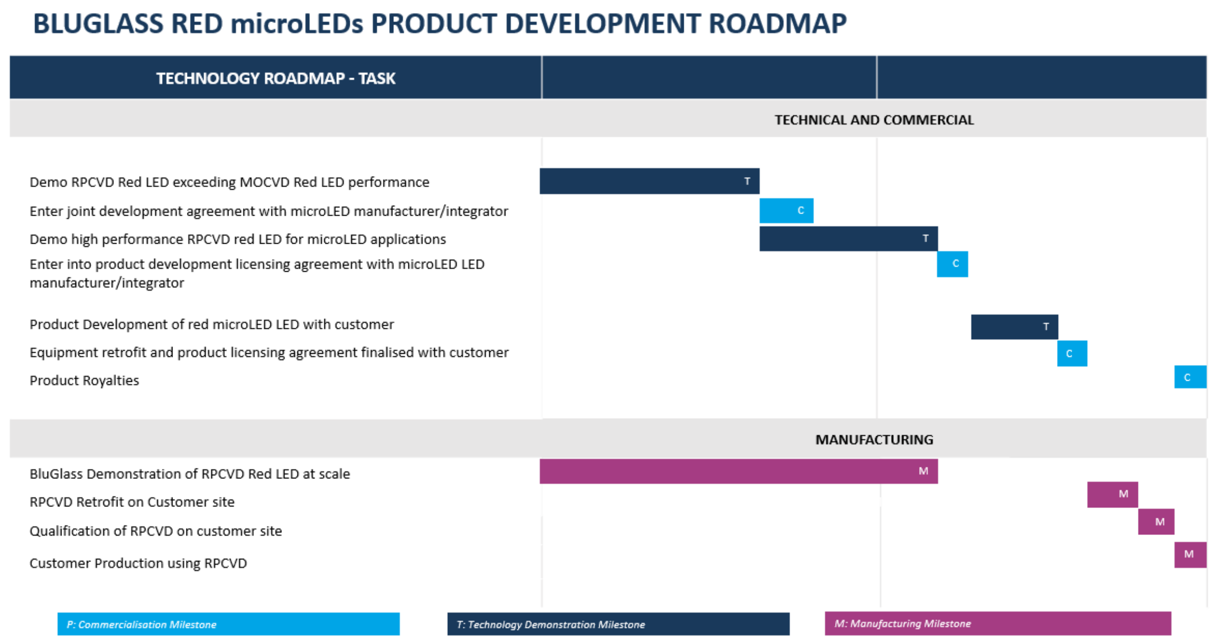


Figure 9: BluGlass Technology Roadmap for Red MicroLED

Potential Technical Barriers to commercialisation	**Action**
The strain in In-rich InGaN/GaN MQWs is intrinsic to the material system, and so no growth process is immune to this issue	Leverage the RPCVD low hydrogen, low temperature growth technology to grow an all InGaN based long wavelength LED structures (using only InGaN layers with varying Indium concentrations) to reduce the strain
Challenges in growing In-rich InGaN/GaN MQWs	Leverage off of existing RPCVD InGaN/MQW development work from blue and green LEDs

Other Potential Barriers to commercialisation	**Action**
Slow to market – MOCVD may improve the InGaN/GaN MQW growth capabilities	RPCVD low temperature p-GaN still presents a significant advantage over high temperature MOCVD-grown p-GaN for preventing thermal damage to the In-rich QWs in red LEDs.

4.5. Laser Diode

BluGlass' RPCVD Tunnel junction (TJ) and other RPCVD GaN processing knowhow can also be exploited through the fabrication of laser diodes. BluGlass' RPCVD TJ enables a unique laser diode design, whereby highly resistive and highly optically absorbent p-AlGaN cladding layers can be replaced with lower resistance and low absorption n-AlGaN layers. This will yield brighter and more efficient GaN based diodes.

Since BluGlass have already established many of the processes needed to form a Laser Diode through their extensive LED work, they expect to rapid progress towards a market ready product. Initial results from the prototypes will provide some clarity regarding the probability of rapid progress.

Laser Diodes			
Figure of Merit	Standard	Key target	BluGlass Performance to date
Brightness (W)	3.5W at 450nm	4W at 450nm	Awaiting the first prototypes currently being fabricated in the US
Vf (V)	5.5 V	5.5 V	

4.5.1. BluGlass Laser Diode Product Roadmap

BluGlass do not intend to license laser diode technology. Using suppliers and process partners to cover the whole laser diode manufacturing process, BluGlass will supply GaN based laser diodes. BluGlass will target cutting and welding sub-section of the laser diode market. Other applications include: display, medical, automotive industries. BluGlass aim to launch first laser diode products to market at the end of calendar year 2020.

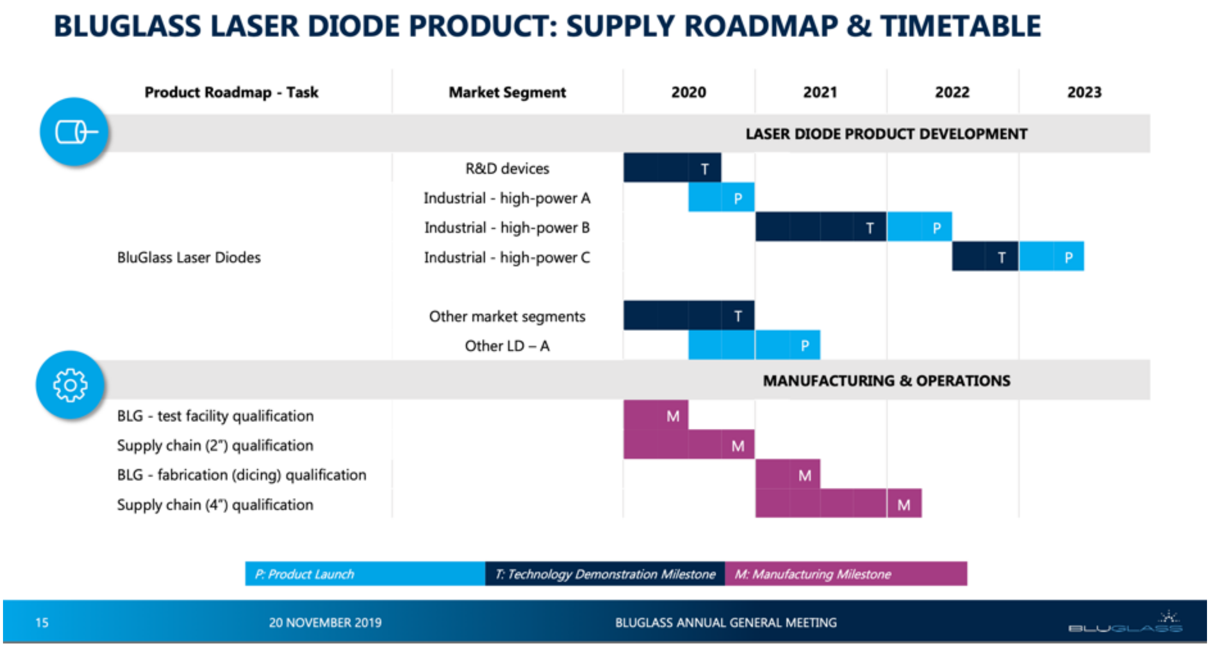
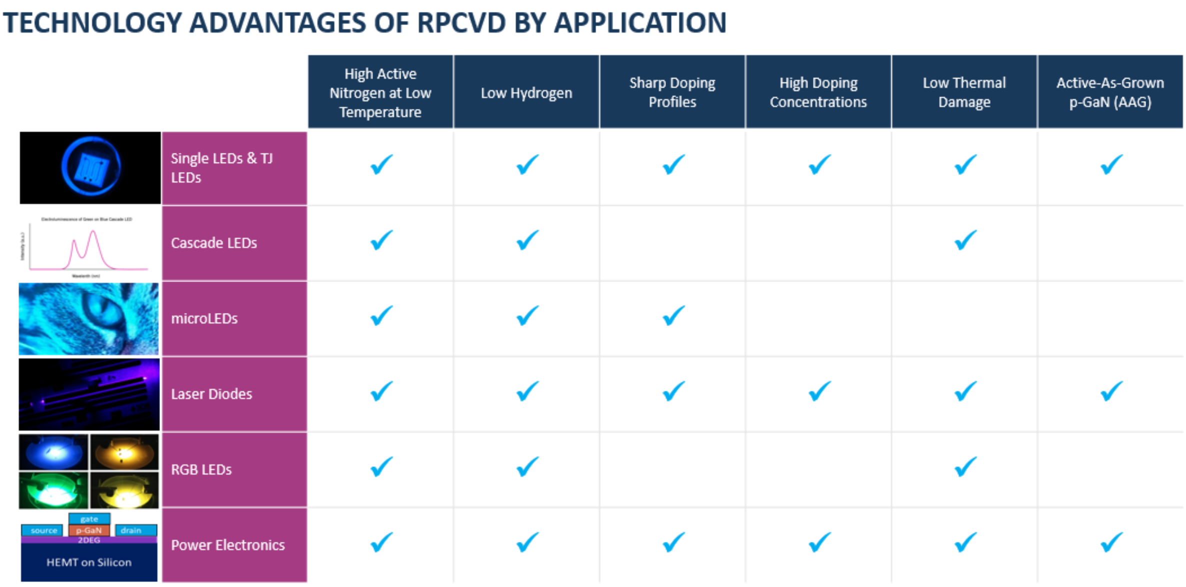


Figure 10: BluGlass Technology Roadmap for RPCVD Laser Diode

Potential Technical Barriers to commercialisation	Action
Long-term reliability	Successfully demonstrate long-term reliability testing & verification. Quality Assurance: Initial 100% LD testing before product shipment
Development delays in proving competitive advantages	Accelerate development iterations with laser diode fabrication suppliers and bring laser diode design capabilities in house. Leverage relevant BluGlass LED development expertise
RPCVD Uniformity	Latest BLG-300 and commercial scale AIX 2800 G4 RPCVD chamber designs will be used for both the development and production of laser diodes.
Substrate supply	Need to ensure reliable and repeatable supply of free-standing GaN substrates (vendor quality can impact LD performance and substitution requires re-qualification)

5. Commercialisation

In this report, we have been exploring how BluGlass are aiming to exploit the advantages of their RPCVD capabilities for a number of applications. Figure 11 summarises the key technology advantages of RPCVD for each application.



TECHNOLOGY ADVANTAGES OF RPCVD BY APPLICATION

	High Active Nitrogen at Low Temperature	Low Hydrogen	Sharp Doping Profiles	High Doping Concentrations	Low Thermal Damage	Active-As-Grown p-GaN (AAG)
Single LEDs & TJ LEDs	✓	✓	✓	✓	✓	✓
Cascade LEDs	✓	✓			✓	
microLEDs	✓	✓	✓			
Laser Diodes	✓	✓	✓	✓	✓	✓
RGB LEDs	✓	✓			✓	
Power Electronics	✓	✓	✓	✓	✓	✓

Figure 11: Low temperature RPCVD benefits by application.

Note that RPCVD also offers a number of additional benefits for other applications including power electronics but these applications are outside the scope of this report.

BluGlass' Commercialisation routes for RPCVD hardware and processes are summarised in Table 2.

BluGlass Key IP Assets		**Commercialisation Activity**
RPCVD Hardware	License	Equipment Design for RPCVD retrofit of commercially available MOCVD kit
	Joint Venture or Joint Development Agreements	(e.g. contract R&D, small number of hardware prototypes etc..)
RPCVD GaN Processes	License	MOCVD/RPCVD GaN based processes and LED based device IP
	Product	New Product Laser Diode.
	Foundry Service	RPCVD epitaxial wafer growth and characterisation services to meet individual customer needs (Trading as EpiBlu)
	Joint Venture or Joint Development Agreements	Contract R&D, test structures or device prototyping etc.

Table 2: BluGlass' commercialisation routes for RPCVD Hardware and RPCVD Processes

5.1. BluGlass' Current Commercialisation Status

BluGlass are currently engaging with several key players in the industry.

There are 3 phases of engagement:

1. Initial evaluation, where external parties request a sample with associated testing and analysis
2. Joint Development Programme
3. Integration

Table 3 outlines current strategic partnerships and evaluation activities.

Company	Type	Business Model (Licencing, Product, Equipment)	Activity
Bridgelux (Kaistar, China Electronics Corporation & Epistar are strategic investors)	Device Manufacturer	License technology	Paid Collaboration for the development of cascade LEDs for general lighting applications. Non-exclusive agreement.
IQE	Manufacturer	Licensing	Epi foundry company exploring RPCVD on cREO for electronics applications. Exclusive collaboration in 2016. Relationship is on-going but on hold as BluGlass concentrates on LED and Laser Diode applications
Luminus (Large LED manufacturer)	Device Manufacturer	Design/Process licensing	Currently unpaid (earlier stage than Bridgelux – potential to move to a paid agreement) Non-exclusive collaboration agreement to co-develop cascade LEDs for the rapidly growing entertainment, display and projector application markets.
Aixtron (Global leader in MOCVD equipment)	MOCVD Equipment	Design/Process licensing	RPCVD equipment and performance evaluation, including evaluating 'bolt on' options. Aixtron and BluGlass are also collaborating on RPCVD retrofit of Aixtron equipment
X-Display (the MicroLED Display spin-off of X-Celeprint)	Technology	Foundry / licensing	Current foundry customer. RGB MicroLED – pick and place, micro transfer.

Table 3: Technology evaluation activities.

The current status of BluGlass’ go to market activity, for both equipment and process applications, are summarised in Figure 12 below.

GO-TO-MARKET ACTIVITY

DEVELOPMENT PROGRAM	END MARKET	EVALUATION	JOINT DEV/ FOUNDRY	COMMERCIALISATION & MANUFACTURING
RPCVD TUNNEL JUNCTION TECHNOLOGY				
Bridgelux JDA	US$6.1B in 2018[1]		✓	
Luminus Collaboration	US$6.1B in 2018[1]		✓	
Continuing HB-LED collaboration discussions	Multiple high-growth market segments	✓		
Laser diode applications	US$14B in 2019[3]	✓	✓	
LED APPLICATIONS				
Continuing HB-LED collaborations	Multiple high-growth market segments	✓		
RPCVD EQUIPMENT				
AIXTRON collaboration & scaling program	MOCVD market to US$1.4B by 2025[1]	✓	✓	
Other capital equipment manufacturers		✓		
microLEDs				
X-Celeprint (now X-Display)	MicroLED market to US$20B by 2024[2]		✓	
EU and USA microLED display manufacturers	Packaged LED market US$16.7B		✓	
OTHER APPLICATIONS				
Leading integrated device manufacturer (IDM)		✓		

Figure 12: BluGlass’ Go-To-Market Activity

5.2. LED Customer Landscape

The global LED chip market is driven by the rising adoption of advanced technologies, including artificial intelligence, automation, the Internet of Things (IoT) and continued expansion in energy efficient lighting. LEDs are increasingly applied in existing and new markets from high-definition large screen displays (TV, laptop), to small displays (watches, mobiles and wearables), to AR and VR headsets, cameras, telecommunications, agricultural applications and optical fiber communications. The automotive industry (higher margin market), followed by general lighting (much lower margin) continues to lead the adoption of LED lighting both in the interior and the exterior segments.

The International Energy Agency (IEA) states that the global LED uptake has increased substantially from a market share of 5% in 2013 to 40% of global residential lighting sales in 2018.

5.2.1. Key LED Market Trends

Government Policies Mandating the Use of Energy-Efficient Lighting

Several policy measures, that mandate the use of LED lights, are expected to drive the adoption of LEDs both in the indoor and outdoor segments. Moreover, the increased investment in infrastructure is likely to lead to the growth of outdoor lighting. National governments and local civic authorities are expected to take advantage of the lower energy consumption and affordability of LEDs to balance out local energy needs and international carbon footprint mandates. Many countries have mandated the use of LEDs as streetlights in order to reduce the fatalities due to poor lighting at the corners and turnings.

Some of the countries (like China), in anticipation of this boom, have pushed for developing more efficient LED production capabilities to be rightly positioned to capture market share in the future. China has started taking the lead in the manufacturing of LEDs as prices of production have fallen to USD 3-5 per lamp, benefiting from substantial financial subsidies and incentives from the government.

Other regions like the EU have made policy regulations to phase out halogen and fluorescent lamps. In 2018, the EU Member States voted to saturate the EU with LEDs by 2021. The EU also introduced minimum performance and quality standards for LED lamps and luminaires across the household, commercial, industrial, and street lighting segment.

Moreover, many countries are trying to rapidly increase the use of LED bulbs in households through direct policy interventions. For example, India has brought a disruptive change in the use of LEDs through its national UJALA program, which uses bulk procurement to offer bulbs that are 50% more efficient than other lamps typically available. In India alone, there have been more than 350 million LED lamps sold since 2015. The program aims to sell 770 million by 2019.

The lion's share of LED market adoption is expected to come out of the Asia-Pacific (APAC) region with China reporting that LEDs now account for 70% of the countries lighting and other countries like India expected to follow-suit.

5.2.2. LED Competitive Landscape

The competitive landscape in the Global LED market remains fragmented, due to the presence of a large number of international and regional actors making the market highly competitive. There are several players that are losing market share due to several emerging entrants from countries like China.

5.2.3. Key LED players:

Key Players in the LED Competitive and Customer Landscape

Figure 13: Some of the top players in the LED lighting market

5.2.4. Key MicroLED players:

The emerging global MicroLED market continues to attract significant investment from both big name technology companies and competitive start-ups in the US, Asia and Europe. The global MicroLED market is projected to grow by US$18.7 Billion from 2020, driven by a compounded growth rate of more than 78%, largely driven by the MicroLED displays segment with continuing strong grow of more than 81% predicted - to reach US$16.2 Billion on its own by 2025. The industry is growing in US, Asia and Europe, with more than 140 players developing their competitive solutions for the displays, augmented and virtual reality markets.

Key Players in the MicroLED Competitive and Customer Landscape

Figure 14: Some of the top players in the MicroLED market

5.3. Laser diodes

The global laser diode market reached a value of US$ 7.61 Billion in 2018. The market is further projected to reach a value of US$ 11.89 Billion by 2024, growing at a CAGR of 7.71% during 2019-2024.

By application the global laser diode market is growing in optical storage and communication applications, industrial and medical applications, military and defense applications, and instrumentation and sensor applications. At present, industrial applications account for the majority of the market share (BluGlass' initial target market).

5.3.1. Global Laser Diode Market Drivers

The industrial laser diode segment continues to gain momentum for material processing applications including metal welding, metal hardening, laser brazing, cladding, and cutting of metals driven by higher precision manufacturing demand in the automotive, aerospace, heavy engineering and consumer electronics industries.
Growing demand for medical laser diodes is another key driver of market growth. High precision targeting and a reduction in evasive surgical techniques sees laser diodes continuously expanding in the spine, throat, cardiovascular and cataract surgeries.
Growing demand in the luxury automotive industry, with laser diodes being increasingly deployed in the manufacturing of automotive headlamps for improved visibility, sight range extension and increased road safety.

The market is fragmented in nature with the presence of numerous small and large manufacturers who compete against one another in terms of prices, quality, and innovation.

5.3.2. Key Laser Diode players

Some of the leading players operating in the market are shown in Figure 15.

Key Players in the Laser Diode Competitive and Customer Landscape

Figure 15: Some of the top players in the Laser Diode market

LED and MicroLED Applications

Figure 16: LED, MicroLED end applications (clockwise from top left): automotive lighting, virtual reality MicroLED display headsets, augmented reality, projector lighting, general lighting, horticultural UV lighting

Laser Diode Applications:

Figure 17: Laser diode applications (clockwise from top left): laser display lighting, industrial cutting applications (x2), medical laser applications, laser welding, automotive laser lighting.

6. Summary and Conclusion

RPCVD is a highly promising deposition technique, with several advantages that can be exploited to compliment industry standard MOCVD growth. MOCVD requires high temperatures to grow good quality, low defect crystalline GaN layers, which is necessary for manufacturing GaN LEDs/Laser Diodes. There is not scope to reduce the temperature of MOCVD GaN for LEDs/Laser Diodes, since this would result in material of inadequate quality and longer process times.

BluGlass have demonstrated that RPCVD can produce good quality GaN at low temperatures, and have ensured they have necessary IP protection in place, securing a strong IP portfolio. They are exploiting their IP, knowhow and expertise in RPCVD growth of GaN for LEDs and GaN Laser Diodes structures. The main advantage of low temperature RPCVD is that it can be used in conjunction with MOCVD to address the limitations of MOCVD, resulting in new lower cost, higher performance, product solutions.

BluGlass have demonstrated growth of structures for devices such as single tunnel junction LED, Cascade LED, MicroLEDs and Laser Diodes. BluGlass' RPCVD tunnel junction technology is of great commercial interest since it can be used in the production of single TJ LED, Cascade LED, and Laser Diodes.

BluGlass' RPCVD equipment design technology has captured the interest of global MOCVD equipment industry leaders Aixtron. Early in 2019, BluGlass signed a joint development agreement, for the evaluation of their RPCVD technology with a mass production-scale MOCVD tool (AIX 2800G4-HT). This activity is due to start mid CY2020. Collaboration with a world leading MOCVD equipment manufacture validates the credibility of the technology, and demonstrates the industry's interest. It is convincing that successful demonstration of RPCVD retrofit on production scale equipment will generate customer demand. However, this activity (starting mid CY2020) is at a fairly early stage, and as such is high risk. At this stage of development, it is not known if successful demonstration can be achieved. Furthermore, the length of time needed to meet the performance specifications required for successful demonstration is unknown. However, BluGlass' have previously demonstrated rapid progress in the development of BLG300 and the development of the mass AIX 2800G4-HT will be carried out in collaboration with Aixtron. This increases confidence that this activity can be successfully realised and expedited.

Although BluGlass' RPCVD target device processes are all relatively early stage R&D, they have attracted the interest of key industry players such as Bridgelux, Luminus and other global players. BluGlass have made excellent progress in engaging with these organisations and forming collaborative development agreements. Clearly, the next step is to further develop RPCVD processes to meet performance targets and to convert the outputs of this development work into revenue through licencing agreements. However, owing early stage nature of the R&D, the length of time it will take to bring single TJ LED, Cascade LED, and MicroLEDs processes to a license-ready stage is unknown and is not simple to predict.

For single TJ LED, and Cascade LED, BluGlass are aiming to commercialise via licensing and are currently working with Bridgelux and Luminus, who may seek first mover advantages. Over the next 6 – 12 months, as more results become available, it will become clearer as to what timescale is realistic. Progression from current performance to license ready processes could involve several development iterations. Typically the progression of research to this level would be managed within a programme of activities implemented over a period of around 2 to 3 years. However, in this case, it is possible that there will be early adoption by the customer (to customise the technology for their specific product roadmaps to gain competitive advantage), rather than wait until full completion of the technology and manufacturing support.

BluGlass are taking a very sensible approach to launching a low volume, high value Laser diode product. They are applying their expertise, knowhow and exploiting their existing IP. BluGlass have already established many of the processes involved in the Laser Diode growth processes, so it seems likely they should advance quickly. However, before the likelihood of rapid progress can be assessed, analysis of the initial performance results from laser diode prototypes will be required. Since BluGlass intend to work with suppliers to cover the whole manufacturing process, significant work will be needed to ensure a high performance, quality product, e.g. repeatability, uniformity, yield and product lifetime. Again, the time to product launch is ambitious. The low volume nature of this business is a good fit with BluGlass capabilities.

Although cost advantages of low temperature, ammonia free RPCVD can be inferred, it has not been possible to quantify the cost advantages of each RPCVD GaN based device. As development progresses towards manufacturing, it is essential to demonstrate a clear understanding of the cost-performance benefits, since this will support the marketability of the process licences.

In summary, BluGlass technology has the potential to realise a number of different higher performance devices, addressing significant market opportunities, such as:

- $6.8B general lighting market (packaged LEDs) (2018),
- $20B MicroLED market (2024),
- $1.4B global MOCVD equipment market (2025)
- US$14B Laser Diode Market (2019)

(Data source: BluGlass November 2019 AGM, which is aligned with other available data).

BluGlass’ engagement of key industry players such as Aixtron, Bridgelux and Luminus lend support to the credibility of the technology and its competitiveness. Furthermore, industrial engagement at this early stage improves the likelihood of successful commercialisation. As is often the case with applied research and development, the risk is high, the time to market is difficult to predict, but the opportunity is considerable.