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# BLUGLASS 2017 AGM

# CHIEF OPERATIONS AND TECHNOLOGY OFFICER'S ADDRESS

## TECHNOLOGY REVIEW

Good morning, my name is Ian Mann and I am the Chief Operations and Technology Officer at BluGlass. Today I will be presenting: 1) a brief overview of the technology progress with our collaborations that we have in place to date, 2) a summary of the various RPCVD differentiators that we are actively pursuing at present including their synergy across our projects and market applications, and 3) a high-level overview of technical progress on several internal projects aiming to deepen our existing industry relationships whilst also attracting new customers and strategic collaborators.

## LUMILEDS AND OTHER INDUSTRY COLLABORATIONS HIGHLIGHTS

We have made good progress over the year working on the Phase II milestones of our collaboration with Lumileds. Both parties are pleased with the progress and remain committed to this key project. We have gone through several device testing iterations and these take time to complete by both parties – BluGlass to grow the materials and Lumileds to fabricate and test the devices.

Earlier this year, in conjunction with Lumileds, we made the decision to pause the efforts on the larger BLG-300 RPCVD system to commence the installation and commissioning of the upgraded chamber. BluGlass, at the time felt confident that the progress on the collaboration was at a sufficient level that warranted this timing for the install, as the project would be advanced by the uniformity and performance improvements anticipated with the new chamber design. I will show the new chamber performance shortly but in summary the chamber upgrade has successfully delivered both improved performance and uniformity results.

To mitigate delays from the upgrade, we diverted efforts on the Lumileds project to our smaller RPCVD chamber, the BLG-180. This had the added benefit of helping speed the re-development once the new BLG-300 was installed as the two new chambers share the identical design, apart from some minor geometry considerations. Upon the completion of the BLG-300 chamber commissioning we immediately recommenced the Lumileds work and were very pleased by how quickly the new chamber was brought up to speed and demonstrating improved results toward the Phase II milestones.

During the year we also focused effort on another key project for the IQE collaboration. This collaboration is ongoing and both companies remain committed to achieving the technology goals. Based on the previous work we completed with the cREO technology, we have been able to make quick initial gains in this project.

We are now active in all our industry collaborations and have recently re-engaged with Veeco and HC Semitek in planning the next steps on the back of the larger RPCVD BLG-300 uniformity progress.

During this period, BluGlass was also able to compile a considerable number of results with unique RPCVD processes and we have recently filed a provisional patent application.

## BLG-300 CHAMBER UPGRADE – THICKNESS UNIFORMITY IMPROVEMENT

Last year we implemented a very successful new chamber design on our smaller RPCVD system (the BLG-180). Taking this improved and successful design, we applied this to a scaled-up, modular design for our larger RPCVD system (the BLG-300). We held off on installing the new chamber for a time due to the progress being made with our industry collaborations.

We were pleased to announce its implementation in August this year and shortly after in September to further announce that it had successfully achieved our target thickness uniformity of <3% across a 4" wafer. The uniformity profile of the BLG-300 is now sufficient for our work with our existing partners. We also have the necessary data to further refine this in the future or for larger platform implementations.

## BLUGLASS CUSTOM EPITAXY SERVICES

While we remain primarily focused on the major players for incorporation of RPCVD, we continue to offer MOCVD services using our on-site MOCVD deposition system. This is primarily helping early stage companies or those that are well established, but looking for a competitive advantage and interested in implementing RPCVD in developing new products. Our service business is also presently generating initial RPCVD repeat revenues predominately from hybrid RPCVD and MOCVD devices (both technologies in a single device) - this is a strategic and important path to get industry feedback and acceptance of RPCVD performance in different practical applications.

BluGlass has published several important new demonstrations; most recently at a nitrides conference earlier this month in the US, to showcase some of the key possibilities of RPCVD. I will touch on some of this work in the upcoming slides.

## RPCVD TECHNOLOGY DEVELOPMENT AREAS

Before I table some of the newer RPCVD results I wanted to explain how synergistic the various technical requirements of RPCVD are, even for a broad range of applications and customers. In this table, of the collaboration efforts that can be disclosed; the double circles represent applications that we are actively collaborating in whereas the single circles are internal projects that prospective customers/collaborators are interested in and that we have allocated some of our internal efforts in the last few months. It is important to note that all the development work that we are conducting at BluGlass is led by industry enquiry.

Most semiconductor devices comprise what is called a ‘stack’ of different types of layers, each having a separate function, and while these layers and stacks are different depending on the application, there are clear commonalities between them. A typical LED, for example, starts with a substrate (such as sapphire or silicon), followed by a GaN buffer layer, followed by an n-type GaN layer. These are followed by the most critical layers: the InGaN MQW active region (where the light is emitted) and the top p-type GaN layer. A high electron mobility transistor (HEMT) device for power electronics also has a similar set of layers, but is different in that there is a critical AlGaN layer towards the top of the structure rather than a MQW active region that drives the performance.

One core commonality between the application of RPCVD for LEDs and for a Normally-Off HEMT is that the p-GaN layer is the final layer to be grown in the stack. In this sense, when developing and improving RPCVD p-GaN, we can be reasonably insensitive to what structures we grow our p-GaN on. This is part of the reason we have been so prolific in our p-GaN efforts – we have a technical advantage in the layer itself, but given it is the top layer in many of the applications it is relatively easy to take an MOCVD grown wafer and then use it as a substrate for RPCVD before going on to be processed into final devices.

Following the same logic, instead of using RPCVD as the top layer, we can also use it on the bottom layer to grow on the substrate and then send the wafers to customers to then grow their full MOCVD structures on the RPCVD coated wafers. It is commercially attractive with RPCVD to focus on either the top or bottom layers in a device structure as opposed to just the central layers alone as this would require that wafers be shipped back and forth multiple times.

The customers vary from LED industries to power electronics, so while there may be little overlap in interest in the final application between certain BluGlass customers, if our process (for p-GaN, for example) is effective for multiple markets it makes sense to exploit those markets as much as possible. For meeting specific customer needs, BluGlass’ MOCVD capability can provide services to fill in the gaps where the optimised solution requires a hybrid approach targeting the specific benefits of both RPCVD and MOCVD to the various layers within the device.

Each market segment, will have an interest where RPCVD has an advantage in more than just one technical aspect – so we are mindful of not just developing a single differentiator across the various markets. RBG LEDs is one good example and I will touch on this later.  BluGlass is exploring multiple RPCVD differentiators in multiple markets where the industry dictates that a low temperature technology could be highly advantageous. This has been determined as our best path to industry acceptance rather than developing a single deep solution for a singular market at our present stage of development.

**RPCVD p-GaN FOR NORMALLY OFF (E-MODE) HEMTs – COLLABORATION WITH VEECO**

On the back of our internal p-GaN efforts we have worked with Veeco on both green LEDs and Normally Off HEMTs for power electronics. We are grateful to Veeco for allowing us to share some of the results of our efforts for power electronics applications.

I won't go into all the technical details for this audience, however I did want to illustrate the primary differentiating mechanism that p-GaN offers for power electronics. The right hand side of this slide shows the concentration profile of magnesium (Mg) atoms through the thickness of the HEMT device. The Mg comes from the p-GaN layer – it is the dopant necessary to make it p-type. It is undesirable to have the Mg diffuse into the critical device performance layer that comprises the AlGaN. This is one of the challenges of making a normally off HEMT device using a top p-GaN layer. As shown here, when the p-GaN is grown by MOCVD at higher temperature more Mg diffuses into the thickness of the layers. When p-GaN is grown using low temperature RPCVD there is significantly less diffusion into the layers. Note that this is materials wafer data only and fabricated devices are needed to ascertain the advantage.

BluGlass is currently working on exploiting this feature in fully working processed HEMT devices. This is a key reason why we have partnered with the Australian Integrated Manufacturing Cooperative Research Centre (IMCRC) and Griffith University to fabricate and test BluGlass' HEMT devices that include RPCVD growth as part of a recently awarded Grant.

**RPCVD p-GaN + MOCVD for Green LEDs -1**

It is worth recapping here the value proposition of low temperature RPCVD p-GaN. This figure shows two simplified LED structures, one grown using only MOCVD and the one of the right shows a hybrid MOCVD stack with a low temperature RPCVD p-GaN layer grown on top. In all LEDs, the p-GaN layer is grown on top of the multi-quantum-well (MQW) region which is made of alternating layers of gallium nitride and indium gallium nitride (InGaN) and it is the MQW that is the active region of the LED critical for light generation.

InGaN, a temperature sensitive material during growth, must be grown at low enough temperatures to incorporate sufficient indium in order to achieve blue, green or yellow light emission. Once the active MQW region has been grown, the next layer to be grown is one of several p-GaN layers (including p-AlGaN) on-top of this temperature sensitive active region. The high temperature growth of p-GaN negatively affects the active region and can degrade the optical performance of the InGaN layers, reducing the efficiency of the quantum-wells and therefore the light output of the LED. This effect is more prominent the larger the temperature difference between the p-GaN and MQW growth temperatures.

Green LEDs require much more indium in the MQW and this layer suffers even more than blue MQWs if overgrown with p-GaN at conventional temperatures. The low temperature RPCVD p-GaN can significantly reduce performance degradation, in particular in green LEDs.

For this demonstration we grow LED wafers on our MOCVD system and measure the performance to compare it with similar LED wafers that are grown under the exact same MOCVD growth conditions, with the exception of the p-GaN layer which we grow using RPCVD. Essentially, we make a partial LED structure with MOCVD that stops above the MQW and then complete the LED by growing p-GaN with RPCVD.

**RPCVD p-GaN + MOCVD for Green LEDs - 2**

I am very pleased to report further year on year performance improvement of our RPCVD p-GaN compared to MOCVD p-GaN for green LEDs. This is from a controlled experiment where we grew partial LED wafers using our MOCVD system. We take two of these MOCVD identical wafers and grow the RPCVD p-GaN layers on one, and MOCVD p-GaN of the same thickness on the other to then measure and compare the final LED wafer performance. The data reported here is using our latest RPCVD BLG-300 system with the upgraded chamber design.

The data presented is measured at our lab using our LED quick test technique but to do the full comparison these need to be fabricated into full working devices of which BluGlass is planning to do. Since we last published data, we have also improved the underlying MOCVD partial LED structures used.

**RPCVD p-GaN + RPCVD MQWs for RGB LEDs - 1**

Another value proposition for low temperature RPCVD is to also grow the multi-quantum well (MQW) active layers. As above, the MQW active region is made of alternating layers of gallium nitride and indium gallium nitride (InGaN) and it is this active region that is critical for the light generation in an LED.

This figure shows two simplified LED structures comparing a full MOCVD grown LED structure and a hybrid MOCVD/RPCVD grown structure, where RPCVD is used to grow both the MQW layers and the p-GaN layers at low temperature.

As previously mentioned, the growth of the MQW active region requires sufficiently low temperatures to incorporate the required amount of indium in the InGaN layers, and the required amount of indium increases as the wavelength of the device increases from blue to green to yellow and towards the red. The longer the required wavelength, the more difficult it becomes to grow the active region with sufficient quality using MOCVD and the more susceptible the active region will be to thermal damage during the growth of the final p-GaN layers.

It is a natural progression from growing just the top p-GaN layers of an LED using RPCVD to growing both the MQW active region and the top p-GaN layers using RPCVD – both of which will benefit from RPCVD and can increase the final device efficiency. We therefore believe that RPCVD can improve the performance of LEDs by increasing the quality and indium incorporation in the active region and then reducing the thermal damage this active region is exposed to during the growth of the final p-GaN layers using the lower growth temperatures of RPCVD.

Green LEDs require much more indium in the MQW and this layer suffers even more than blue MQWs if overgrown with p-GaN at conventional temperatures. The lower growth temperatures of RPCVD enable us to minimise any temperature difference between the p-GaN and MQW growth. This reduces limitations on how much indium can readily be incorporated in the active region and enables us to optimise the structure of the active region to maximise the performance and then tailor final p-GaN layers to reduce the subsequent efficiency degradation of the MQWs, therefore improving the light output of the LED.

## RPCVD p-GaN + RPCVD MQWs for RGB LEDs – 2

Last year we showed some of our initial efforts in growing RPCVD InGaN MQW based LEDs. We are pleased to show the significant progress in recent months and that we have been achieving these types of results on both of our modern RPCVD systems. While we still have a considerable way to go to match the performance of MOCVD blue and green LEDs, our MQWs progress has come quickly over the course of approximately two months of dedicated effort - rapid progress that we aim to continue.

## RPCVD RGB FOR MICRO-LEDs AND SOLAR APPLICATIONS

We are also very pleased to share a step forward with some successful initial trials at growing multi-colour LEDs, from the blue wavelength all the way through to the red. One potential application is for red-green-blue (RGB) LEDs, which are of increasing interest for micro-LED applications such as wearables (watches), mobile phone displays, large TV displays and virtual/augmented reality products.

These results are normalised data and it is critical to note the overall brightness of these initial LED trials is quite low for the longer wavelength samples, but it is a good indicator of the advantages of low temperature in incorporating varying degrees of indium in its MQW layers. BluGlass will continue to develop this capability.

This ability to 'tune' the indium content in also critical for an InGaN solar cell to match and absorb a broad range of light wavelengths (from blue to red) in a multi-junction solar – these results represent a first step towards enabling the capture of a large portion of the solar spectrum.

## THANK-YOU

Once again, I would like to personally acknowledge and thank the BluGlass technology team and support staff for their year of hard work and very dedicated effort. Thank you for your attention today.