04 February 2020

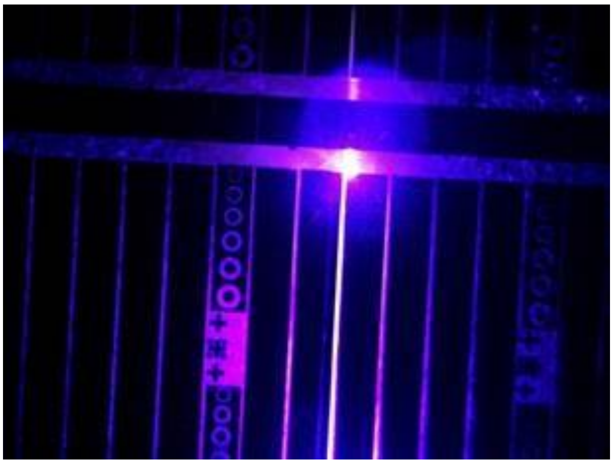
BluGlass presents RPCVD paper at Photonics West 2020 – TECHNICAL SUMMARY & PRESENTATION

Key Points

- BluGlass presents new paper at SPIE Photonics West in San Francisco, USA
- RPCVD GaN tunnel junction laser diode structures show scope for significant conversion efficiency improvements in simulation results
- RPCVD tunnel junction data for LEDs demonstrate strong promise to enable these improved laser diode structures that meet strict growth requirements, not available using industry standard processes

Australian semiconductor developer BluGlass Limited (ASX: BLG) has today presented a new paper at **SPIE Photonics West** in San Francisco, USA (www.spie.org), the leading global event for the photonics and laser industries. The paper presents BluGlass' recent laser diode (LD) development work, utilising the company's unique 'active-as-grown' (AAG) tunnel junctions to improve conversion efficiency in lasers.

BluGlass Head of Epitaxy, Dr Josh Brown presented the paper titled '*High Brightness-MOCVD Laser Diodes using RPCVD Tunnel Junctions'* on the benefits of BluGlass' proprietary Remote Plasma Chemical Vapour Deposition (RPCVD) and tunnel junction technologies for the manufacture of laser diodes.



RPCVD offers laser diode manufacturers a number of performance and cost advantages for the manufacture of high-brightness GaN laser diodes, including higher performing devices with reduced optical loss, and productivity and cost improvements.

RPCVD is a low-temperature, ammonia-free approach to GaN-based epitaxial growth, with advantages not possible with conventional metal-organic chemical vapour deposition (MOCVD).

One of these fundamental differences is BluGlass' unique AAG tunnel junction capability. AAG tunnel junctions can enable novel laser diode structures to reduce the significant optical and resistive losses associated with GaN based laser diodes today.

Tunnel junctions in LDs can be used to replace the heavily lossy (optical and resistance) p-type layers (both the p-AlGaN cladding layer and the p-Ohmic contact layers) in the laser diode with significantly less lossy and less resistive n-type device layers.

High-brightness GaN laser diodes are used in a growing number of applications that include industrial lasers (cutting and welding), automotive and general lighting, displays, and life sciences.

The technical presentation outlines BluGlass' latest development including laser diode technical simulations, tests and preliminary experimental findings. These initial results demonstrate the technical promise of RPCVD tunnel junctions to realise novel higher-performing laser diode structures by reducing optical loss and series and contact resistance.

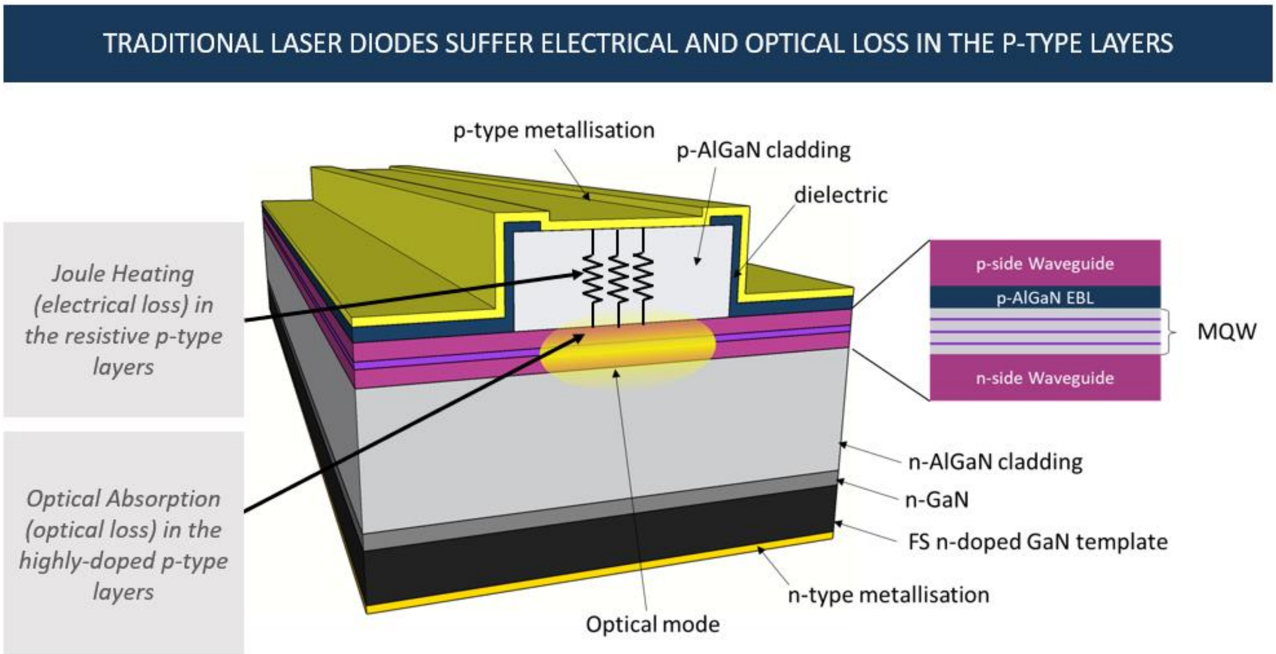
These technical points are summarised for our shareholders below:

Traditional Laser Diodes suffer from significant optical and resistive loss with efficiencies still around 45%

Today, GaN laser diodes (LDs) suffer from significant optical and resistive loss in the magnesium-containing layers (p-type layers) and this leads to low conversion efficiencies, with conversion efficiencies of even state-of-the-art GaN-based laser diodes in the 45% range compared to the 90% approached in GaN-based LEDs (see Figure 1). At high current densities Joule heating from contact and series resistance can account for up to 50% of the power consumed in GaN based laser diodes. This loss occurs in the p-type layers of the device.

To accelerate the use of GaN laser diodes, enhanced development such as extended wavelength range, power levels, efficiency and brightness will be required to make new markets and applications a reality.

Industry effort in recent years has focused on improving the efficiency and brightness of GaN-based laser diodes (LD) to meet the high-performance requirements, however improvements will need to be made in the device structures in order to address these challenges.

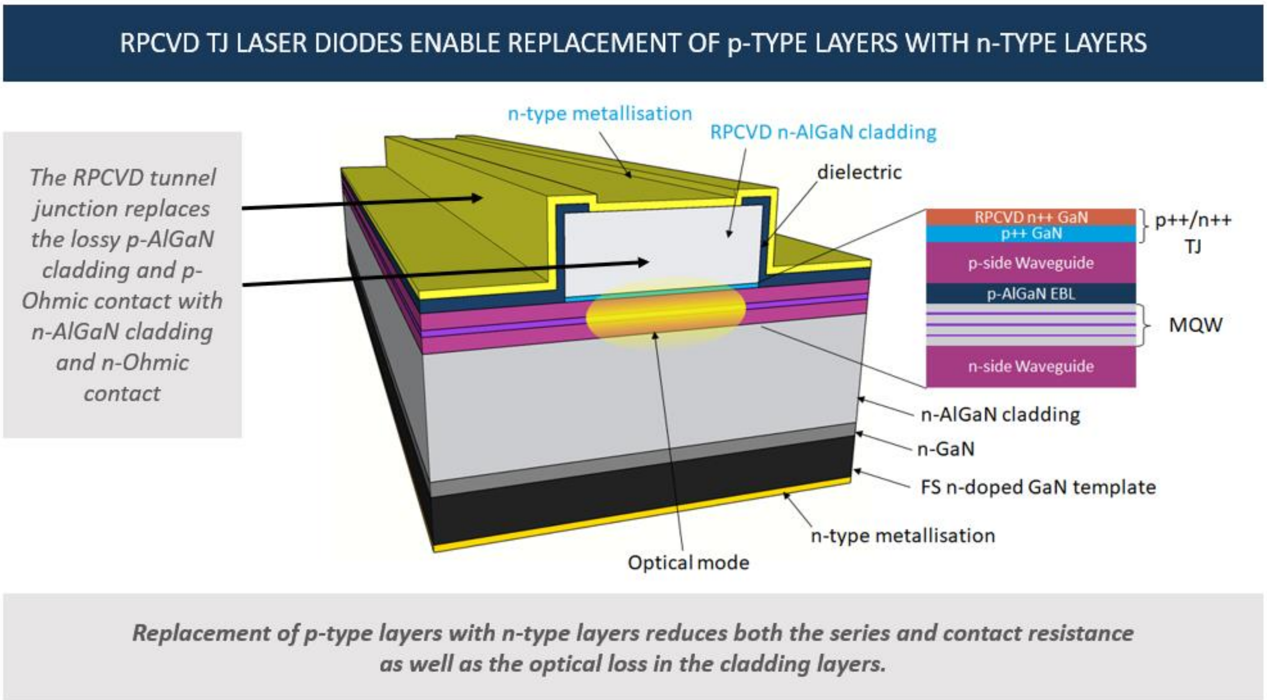


RPCVD's low temperature, ammonia-free GaN deposition platform could hold the key to addressing these fundamental challenges of electrical and optical loss in traditional laser diodes.

Creating novel Laser Diodes structures using RPCVD Tunnel Junctions to address optical and resistive loss

One of the key benefits of the RPCVD growth platform for LDs is its unique 'active-as-grown' (AAG) buried p-GaN technology, that enables high performance tunnel junctions, without the need for ex-situ annealing or processing for magnesium acceptor activation (a critical building block of a tunnel junction). Originally developed for the use in LEDs,

BluGlass plans to address this severe optical loss by using RPCVD tunnel junctions in the laser diode device to replace these resistive and 'lossy' p-type layers with n-type layers to significantly reduce the optical and resistive loss and therefore improve the conversion efficiency of laser diode devices (see Figure 2 below).



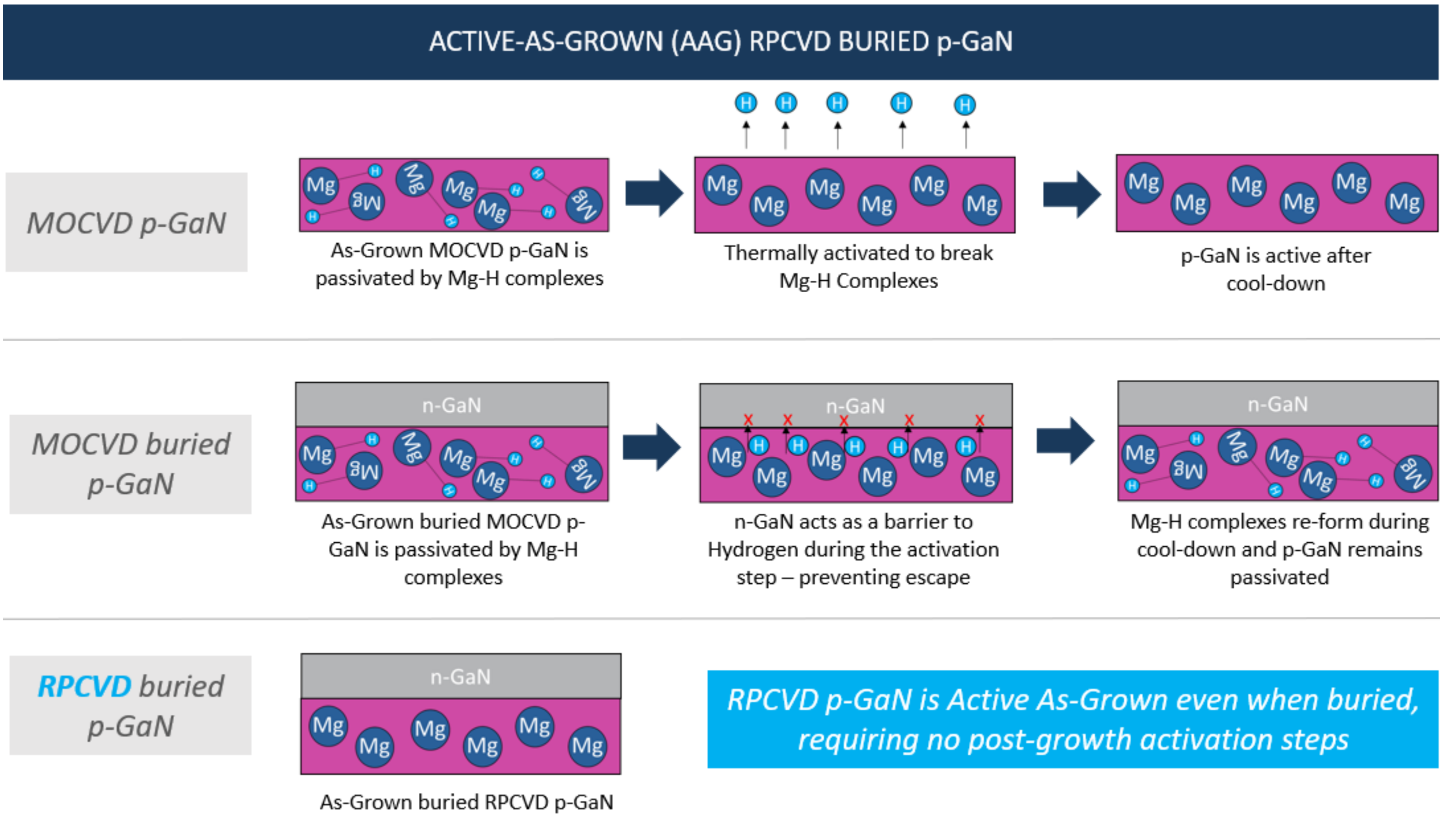
RPCVD's unique low temperature and low hydrogen growth provides the ideal growth environment for tunnel junctions in laser diodes

RPCVD's unique low temperature and low hydrogen growth provides all the necessary building blocks to achieve this over the industry incumbent process metal organic chemical vapour deposition (MOCVD) (see figure 3).

Requirements for n^{++} GaN / p^{++} GaN TJs	RPCVD
High Doping for both n^{++} GaN and p^{++} GaN	✓
Sharp Doping profile at TJ interface – particularly for Mg	✓
Buried Activated As-Grown (AAG) p-GaN	✓
RPCVD displays all the critical building blocks for Tunnel Junctions	

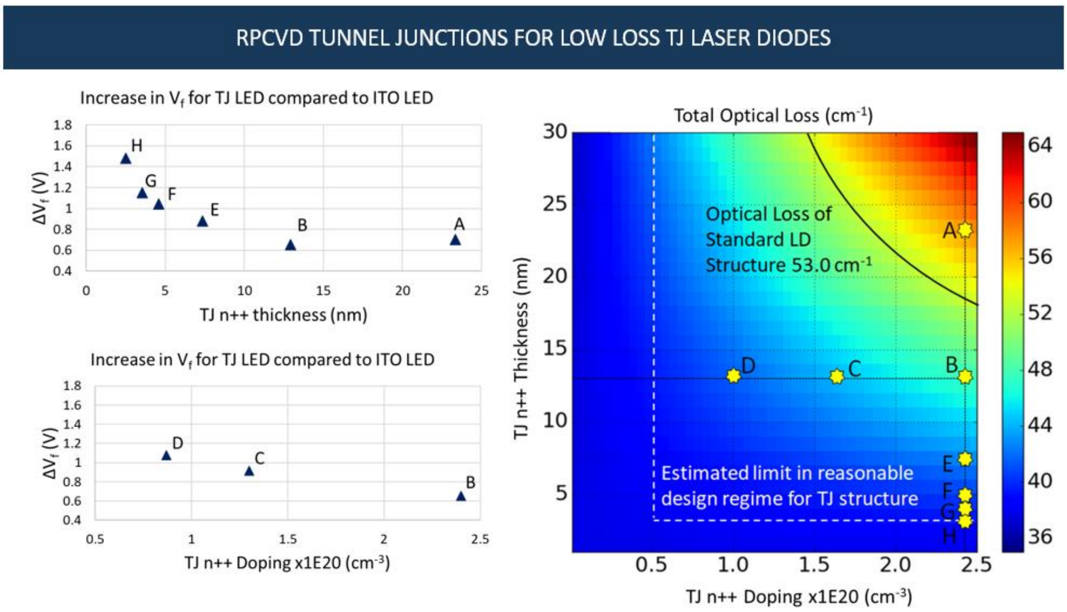
BluGlass has shown that RPCVD can grow active-as-grown (AAG) tunnel junctions (TJ) (see figure 4 below) as a means of producing cascade LEDs to solve the challenges of efficiency droop in high-performance LEDs. The same technology and techniques can be applied to LDs, to replace the p-metal ohmic contact with a lower-resistivity n-type ohmic contact enabled by a GaN-based TJ for conversion between n-type and p-type regions, eliminating the high p-side contact resistance that plagues conventional LD designs.

BluGlass' 'active-as-grown' technology is a key advantage of RPCVD's low temperature and low hydrogen growth environment not available to traditional MOCVD growth techniques.



RPCVD tunnel junctions for LEDs demonstrate applicability for laser diode performance improvement

However, in contrast to tunnel junctions for cascade LED and indium tin-oxide (ITO) replacement, tunnel junctions for laser diode applications have a strict requirement that the tunnel junction itself must not contribute additional optical losses to the device, as other researchers have observed with MOCVD laser diode tunnel junction simulations.



BluGlass performed simulation work to identify the RPCVD requirements of the tunnel junction in order to ensure that the total optical loss of the RPCVD tunnel junction laser diode will be lower than the conventional MOCVD laser diodes.

BluGlass has also experimentally demonstrated, using tunnel junction LEDs, that our RPCVD TJs can be grown within the strict structural constraints required to meet the low optical loss requirements and deliver improved laser diode device performance.

Figure 5 B (above, right) shows the locations of the simulated total optical loss for the tunnel junction LDs using the TJ structures that were tested. Critically, the simulated laser diode using the tunnel junction with the lowest forward voltage of 0.65 V (sample B) lies below the 45.7 cm-1 contour line, with a total optical loss of 43.4 cm-1.

This indicates, as expected, that the forward voltage optimised RPCVD n++/p++ TJ can be successfully used in the laser diode to yield a net reduction in total optical loss. This paves the way for the new device structure to significantly reduce the Joule heating, which occurs in the replaced p-type lossy layers. Joule heating can account for up to 50% of the total power consumption in a laser diode through series and contact resistance losses.

Next Steps

BluGlass is now working on combining the optimised tunnel junction structure with its laser diode structure to demonstrate the advantages of the tunnel junction laser over conventional LDs.

The initial results presented today at SPIE Photonics West demonstrate the technical promise of RPCVD tunnel junctions to provide the potential for an optimised tunnel junction laser diode to significantly reduce the power loss associated with Joule heating and to reduce the total optical loss. This provides a viable path to achieving large gains in GaN laser diode conversion efficiencies well beyond their current 45% limitations and closer towards the values currently only achievable in GaN LEDs.

The BluGlass team continues to improve laser diode performance with bespoke solutions for our existing customers, and we look forward to working with new laser diode developers to bring high-brightness RPCVD-enabled laser diodes to market across a number of applications.

BluGlass is also exhibiting at the SPIE Photonics West conference (Booth 4783), San Francisco 1-6 February at the Moscone Centre.

A copy of Dr. Brown's technical presentation follows below:

About BluGlass

BluGlass Limited (ASX: BLG) is a global leader commercialising a breakthrough technology using Remote Plasma Chemical Vapour Deposition (RPCVD) for the manufacture of high-performance LEDs and other devices. BluGlass has invented a new process using RPCVD to grow advanced materials such as gallium nitride (GaN) and indium gallium nitride (InGaN). These materials are crucial to the production of high-efficiency devices such as power electronics and high-brightness (LEDs) used in next-generation vehicle lighting, virtual reality systems and device backlighting.

The RPCVD technology, because of its low temperature and flexible nature, offers many potential benefits over existing technologies including higher efficiency, lower cost, substrate flexibility (including GaN on silicon), and scalability.

For More Information Contact: Stefanie Winwood +61 2 9334 2300 swinwood@bluglass.com.au

HIGH BRIGHTNESS MOCVD-GROWN LASER DIODES USING RPCVD TUNNEL JUNCTIONS

Dr Josh Brown

Head of Epitaxy – BluGlass Limited

jbrown@bluglass.com.au

3 February 2020

SPIE Photonics West

LASE 2020 – San Francisco

BLUGLASS

FORWARD LOOKING STATEMENT

This document has been prepared by BluGlass Limited to provide readers with an update of the Company and the Company's technology.

Any statements, opinions, technical data and information, or other material contained in this document, do not constitute commitments, representations or warranties by BluGlass Limited or associated entities, or its directors, agents and employees. Except as required by law, and only to that extent, directors, agents and employees of BluGlass Limited disclaim any loss, claim, demand, damages, costs or expenses of any nature whatsoever arising in any way out of, or in connection with, the information contained in this document.

This document includes certain information which reflects various assumptions, subjective judgment and analysis, and is subject to significant business, economic and competitive uncertainties, risks and contingencies, many of which are outside the control of, and are unknown to, BluGlass Limited. The assumptions may not prove to be correct. Recipients of the document must make their own independent investigations, consideration and evaluations prior to making any decisions to invest in the Company.

Information on Service Addressable Markets (SAM) is based on internal BluGlass modelling and assumptions, both of which depend on successful R&D outcomes and results achieved within estimated timetables. BluGlass recommends a cautious interpretation be taken by investors.

ACKNOWLEDGEMENTS

BLUGLASS LIMITED

- S. Barik, Q. Gao, B Siskavich, M. Wintrebert-Fouquet, A. J. Fernandes, P. P. -T. Chen, I. Mann
- D. Timoney, S Chiappa, S. O'Farrell, A. Burgess, C. Byrnes, I. Cruz, T. S. Ho, B. Zadrozny

UNIVERSITY OF NEW MEXICO

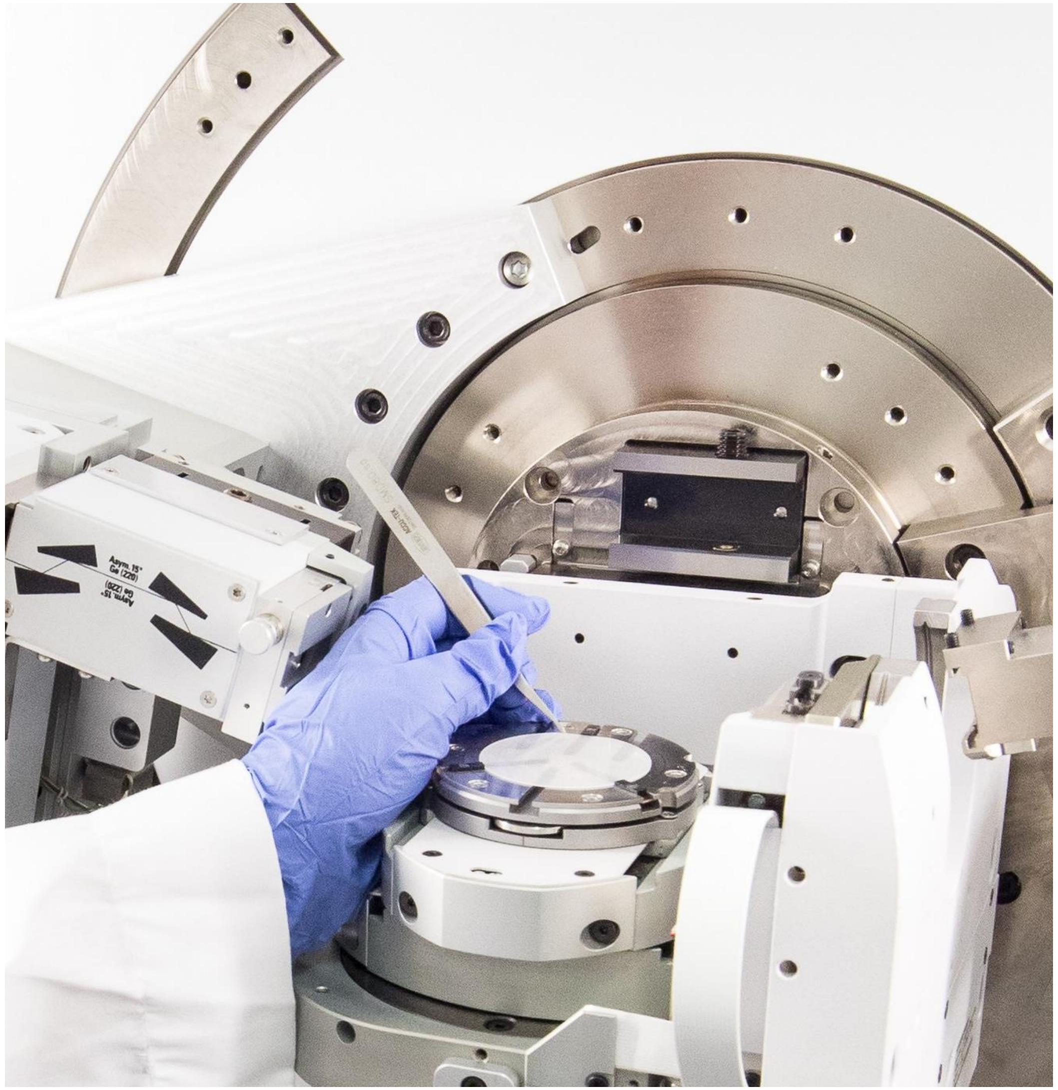
- M.Behzadirad, A. K. Rishinaramangalam, D. Feezell

MOCVD SOLUTIONS LTD, UK

- Laurence Considine

OUTLINE

- BluGlass Limited Overview
- Introduction to RPCVD
- How to Increase LD Conversion Efficiencies
- RPCVD for Tunnel Junctions
- Tunnel Junction Laser Diodes
- Future work



BLUGLASS OVERVIEW

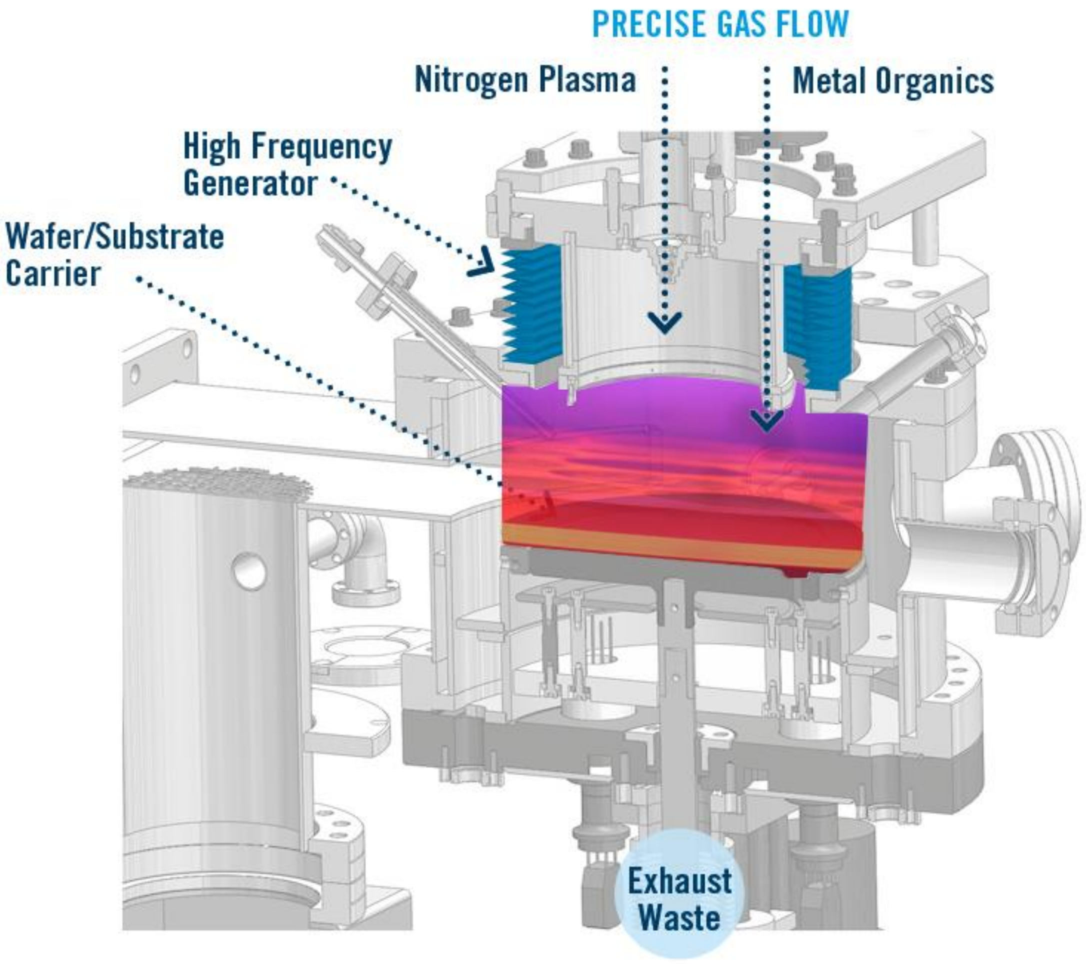
AUSTRALIAN SEMICONDUCTOR DEVELOPER

- Established in 2006, BluGlass was spun out of Macquarie University in Sydney and **listed on the Australian Stock Exchange: ticker ASX: BLG**
- BluGlass is developing its breakthrough **Remote Plasma Chemical Vapour Deposition (RPCVD) technology** as a platform solution with performance benefits for LED, uLED, LD and HEMT applications
- Our subsidiary, **EpiBlu offers a a full suite of RPCVD, MOCVD and hybrid growth custom** epitaxial and characterisation services for customers around the world
- BluGlass has **five deposition systems** onsite at its Sydney facility, including three RPCVD deposition reactors (including the AIX-2800 G4, currently being retrofitted to RPCVD mode with our collaboration partner AIXTRON) and one standard MOCVD platform
- BluGlass has a growing patent portfolio comprising **68 internationally granted patents** covering the RPCVD process, hardware and novel applications

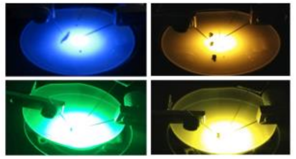
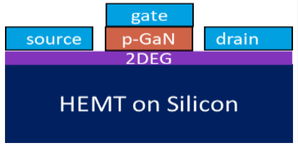
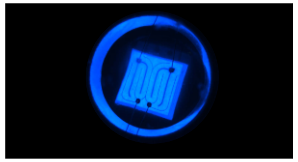
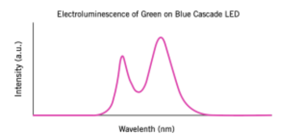
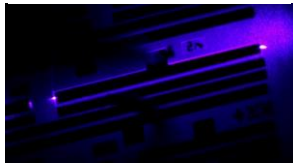
BLUGLASS RPCVD III-NITRIDE TECHNOLOGY

RPCVD combines the scalability of MOCVD with the unique benefits of a nitrogen plasma source

OUR SOLUTION	
	Low-temperature, low hydrogen manufacturing processes, several hundred degrees cooler than MOCVD
	Active nitrogen density, from plasma source independent from growth temperature
	Higher-performing devices
	Lower cost inputs and **reduced** waste

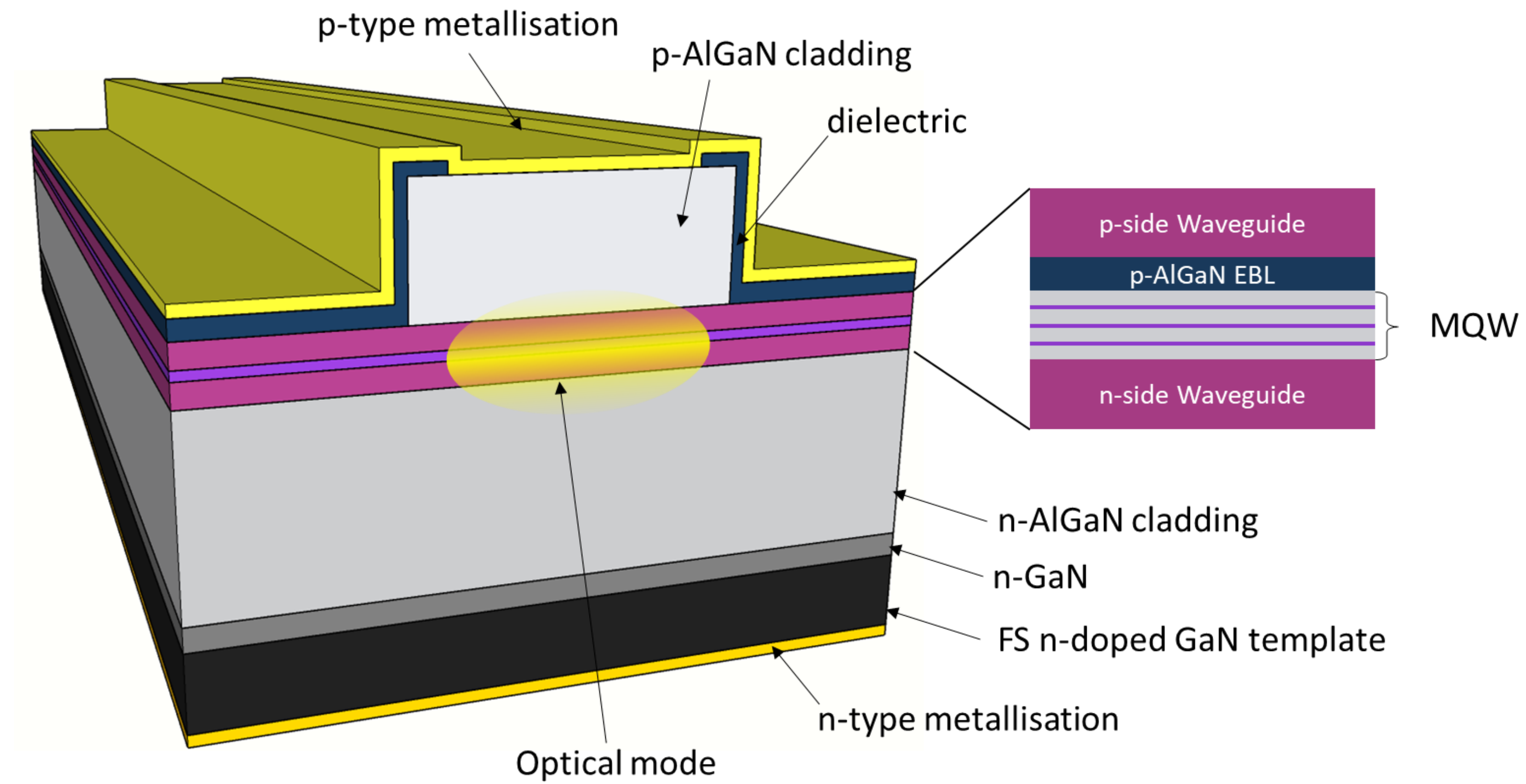


RPCVD BENEFIT BY APPLICATION

		High Active Nitrogen at Low Temperature	Low Hydrogen	Sharp Doping Profiles	High Doping Concentrations	Low Thermal Damage	Active-As-Grown p-GaN (AAG)
	InGaN for RGB uLEDs	✓	✓			✓	
	p-GaN for uLEDs	✓	✓			✓	
	p-GaN for HEMT	✓	✓	✓			
	TJs for ITO replacement	✓	✓	✓	✓	✓	✓
	TJs for cascade LEDs	✓	✓	✓	✓	✓	✓
	TJs for LDs	✓	✓	✓	✓	✓	✓

GaN-BASED LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?

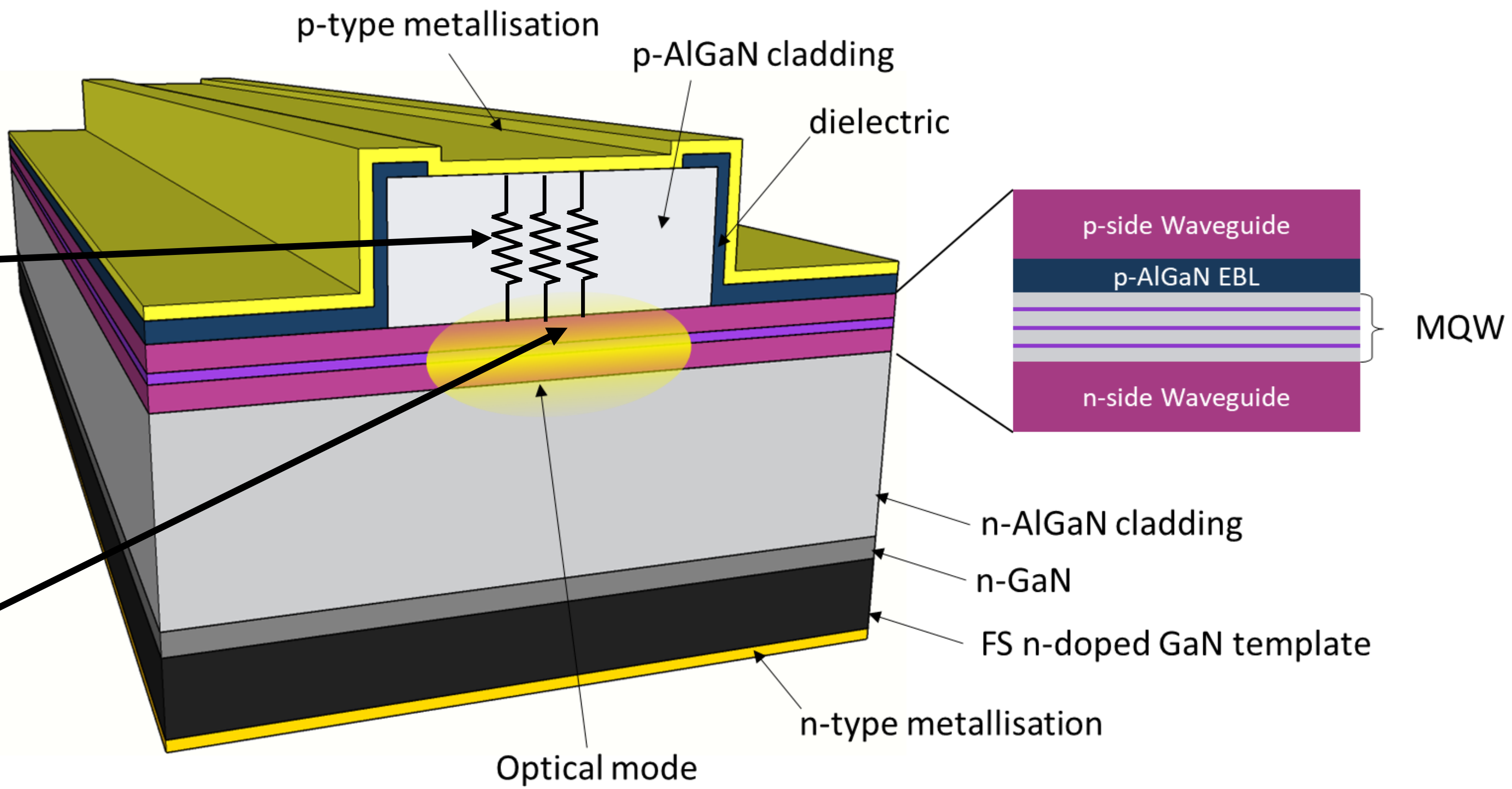


GaN-BASED LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?

Joule Heating (electrical loss) in the resistive p-type layers

Optical Absorption (optical loss) in the highly-doped p-type layers

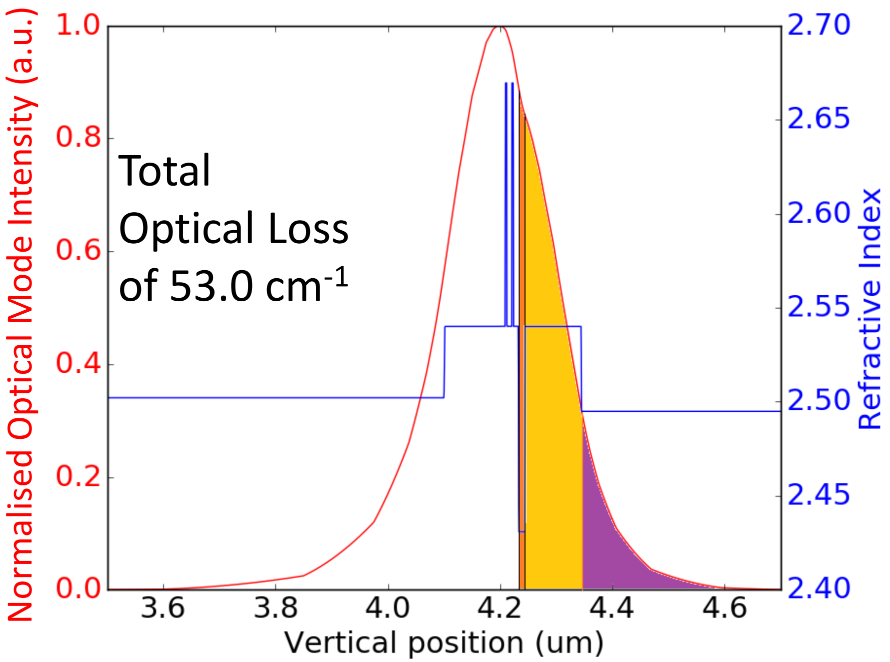


GaN-BASED LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?

Layer	Thickness (nm)	Doping (cm^{-3})	Composition	Abs. Coef. (cm^{-1})	Optical Loss (cm^{-1})
p++ contact	20	1.5E20	GaN	375	0
p-AlGaN cladding	500	1.0E20	$Al_{0.08}Ga_{0.92}N$	250	**18.8**
p-WG	100	2.0E19	GaN	50	**11.9**
EBL	12	1.5E20	$Al_{0.2}Ga_{0.8}N$	375	**14.7**
2x InGaN/GaN MQW	2.7 / 9.0	-5.0E16	$In_{0.11}Ga_{0.89}N$ / GaN	12	1.4
n-WG	100	-2.0E17	GaN	12	4.0
n-AlGaN cladding	1000	-3.0E18	$Al_{0.067}Ga_{0.933}N$	12	2.2

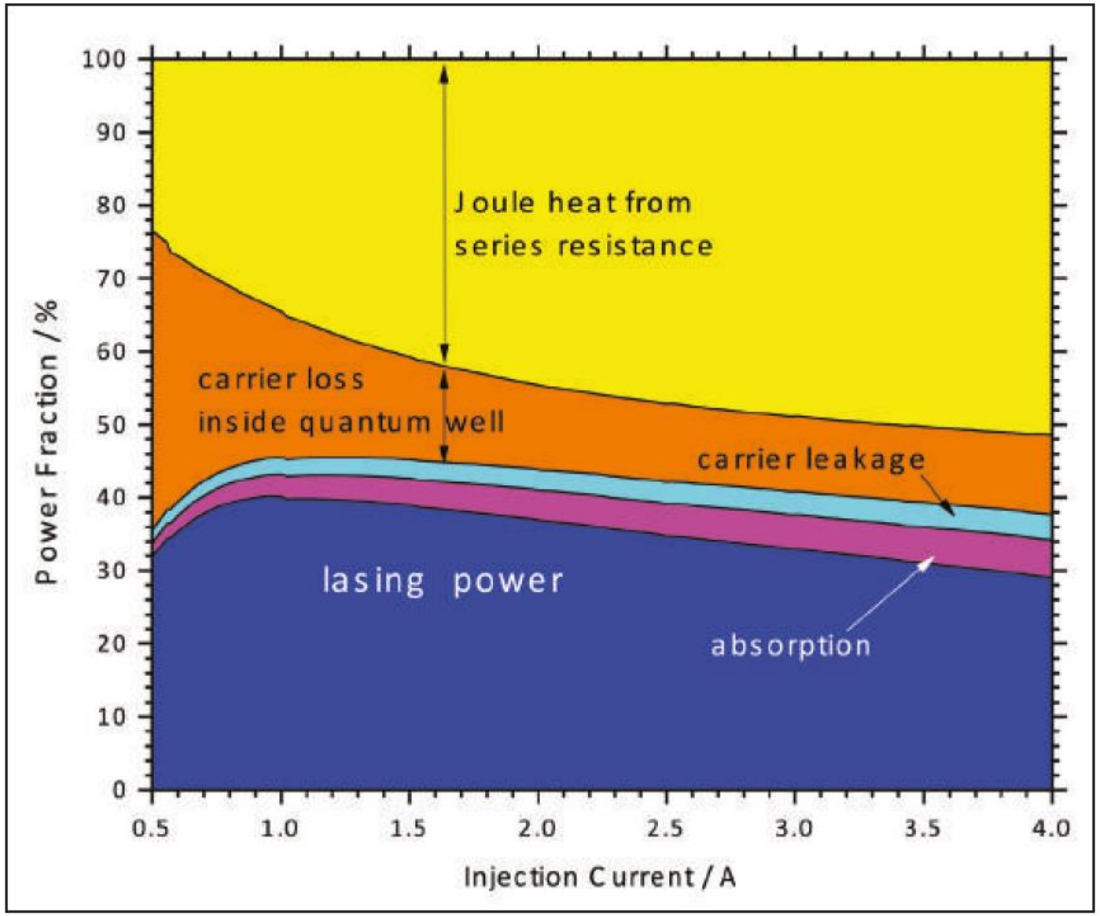
Simulation of optical mode and refractive index profile of MOCVD Laser Diode



Optical Absorption in the p-type layers can account for > 80% total optical loss

GaN-BASED LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?



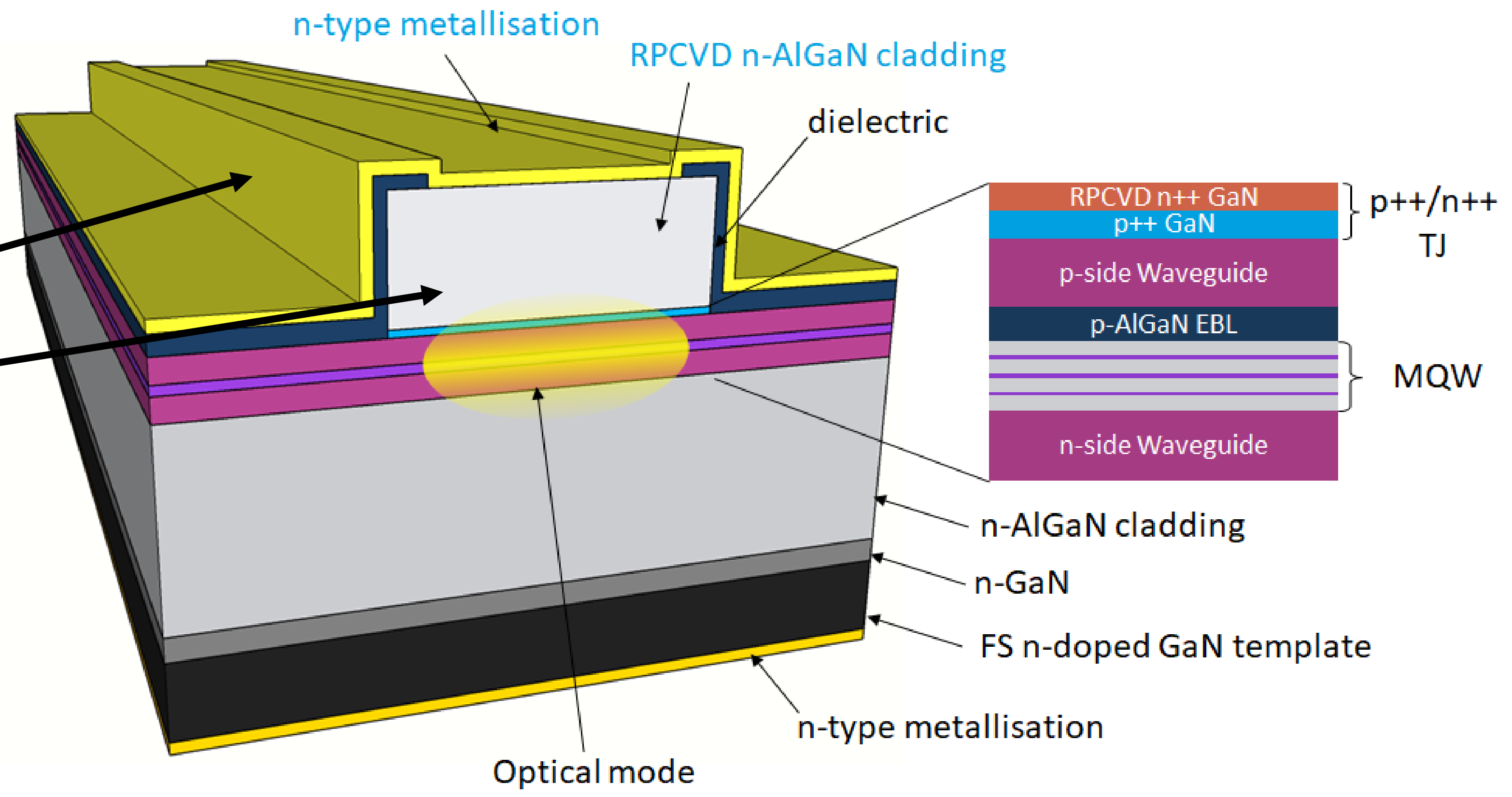
At high current densities, Joule heating from series and contact resistance can account for up to 50% of the power consumed in GaN-based Laser Diodes

Source: Piprek, J., "What is to blame for the low efficiency of GaN-based lasers?," Compd. Semicond.(July), 3, 35–38 (2017).

HYBRID MOCVD/RPCVD TUNNEL JUNCTION LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?

Tunnel Junction Laser Diode (TJLD) structure replaces the p-AlGaN cladding and p-Ohmic contact with n-AlGaN cladding and n-Ohmic contact



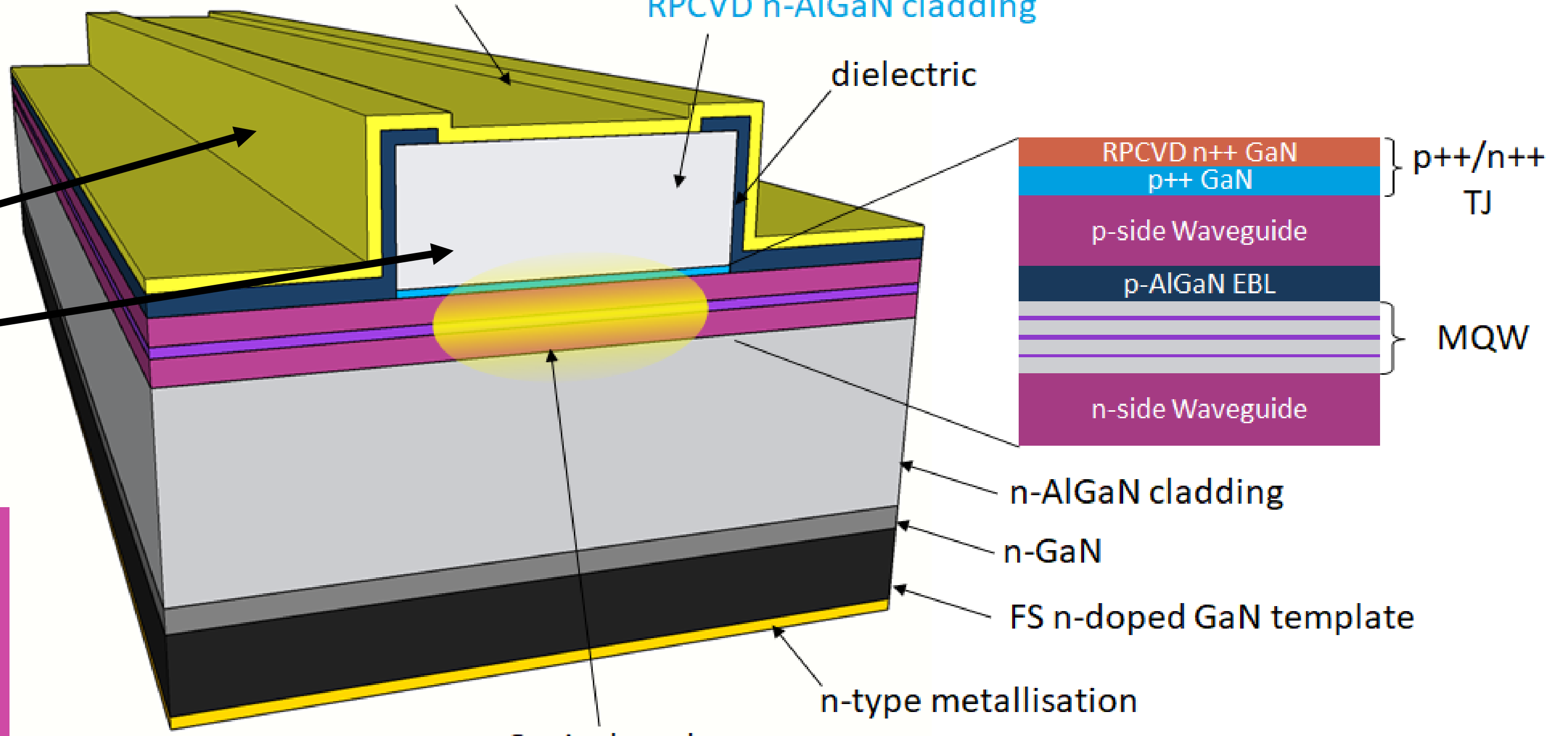
Replacement of p-type layers with n-type layers **reduces both the series and contact resistance** as well as the optical loss in the cladding layers

HYBRID MOCVD/RPCVD TUNNEL JUNCTION LASER DIODES

How to improve the low conversion efficiency of GaN-based Laser Diodes?

Tunnel Junction Laser Diode (TJLD) structure replaces the p-AlGaN cladding and p-Ohmic contact with n-AlGaN cladding and n-Ohmic contact

What about the optical losses in the TJ?

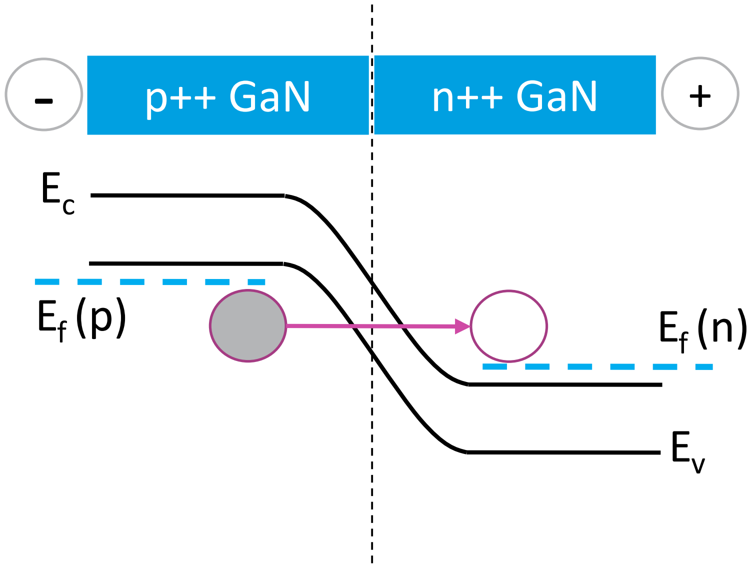


Replacement of p-type layers with n-type layers **reduces both the series and contact resistance** as well as the optical loss in the cladding layers

GaN TUNNEL JUNCTIONS

$$\omega \propto \sqrt{\frac{E_g(N_A + N_D)}{N_A N_D}}$$

Wide bandgap material ↔ *GaN has wide depletion width*



Electron ↔ Hole carrier conversion

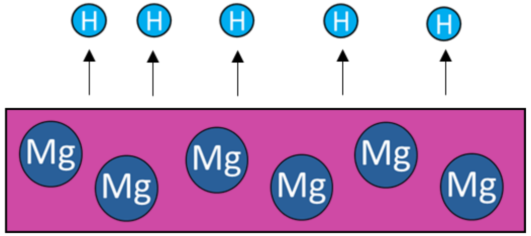
Requirements for n^{++} GaN / p^{++} GaN TJs	RPCVD
High Doping for both n^{++} GaN and p^{++} GaN	✓
Sharp Doping profile at TJ interface – particularly for Mg	✓
Buried Activated As-Grown (AAG) p-GaN	✓

RPCVD displays all the critical building blocks for Tunnel Junctions

ACTIVE AS-GROWN RPCVD BURIED p-GaN

MOCVD p-GaN

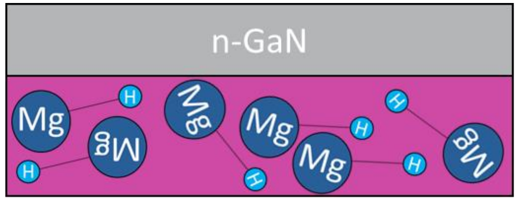
As-Grown MOCVD p-GaN is passivated by Mg-H complexes



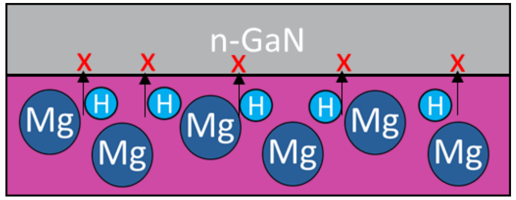
Thermally activated to break Mg-H Complexes

p-GaN is active after cool-down

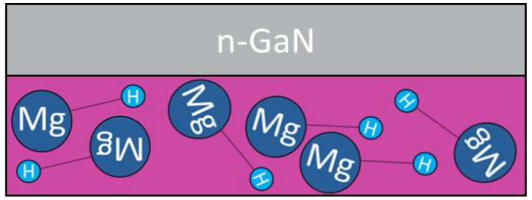
MOCVD buried p-GaN



As-Grown buried MOCVD p-GaN is passivated by Mg-H complexes

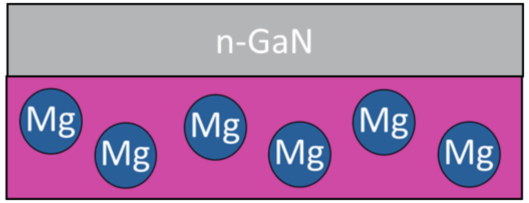


n-GaN acts as a barrier to Hydrogen during the activation step – preventing escape



Mg-H complexes re-form during cool-down and p-GaN remains passivated

***RPCVD** buried p-GaN*

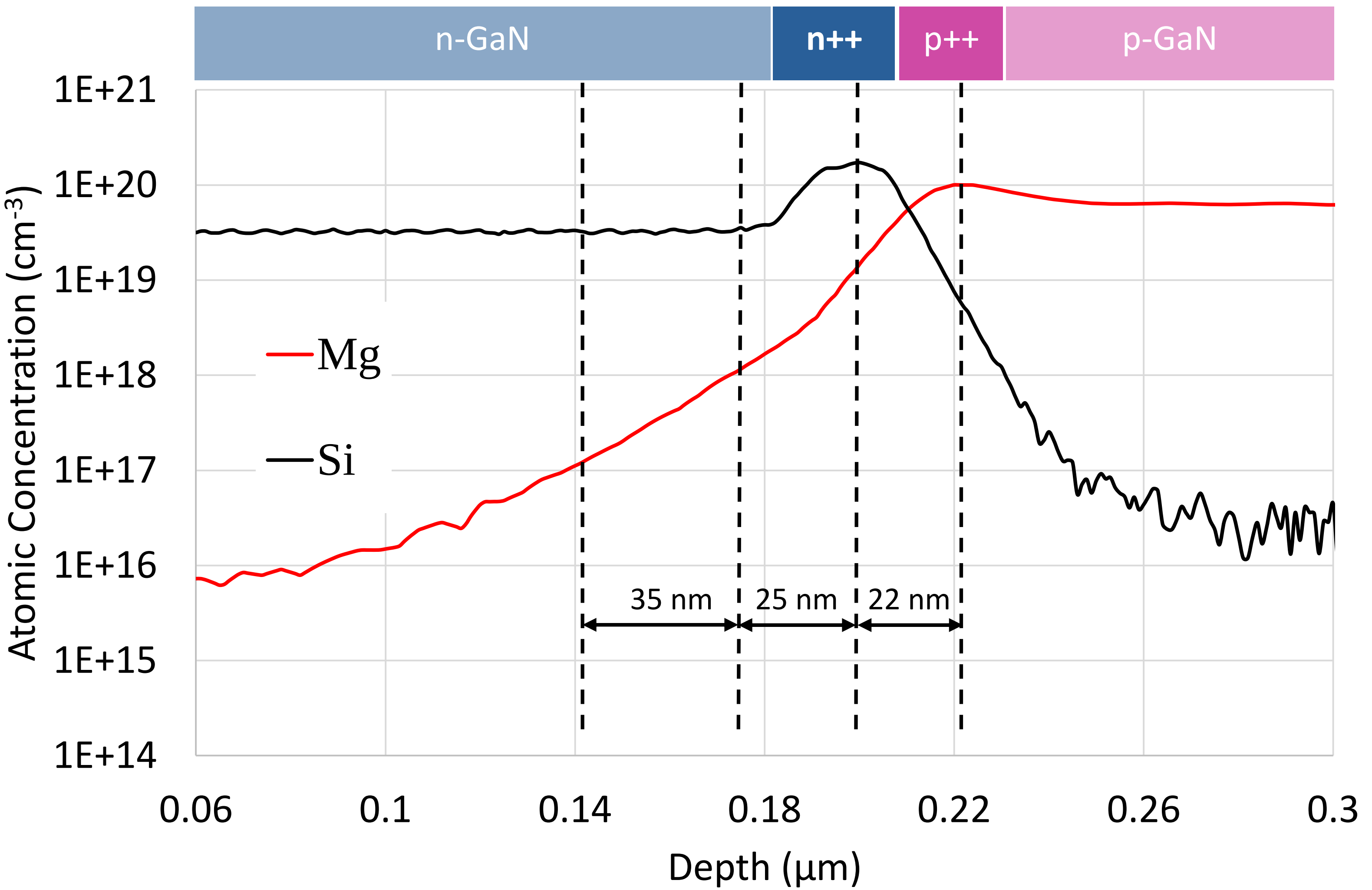


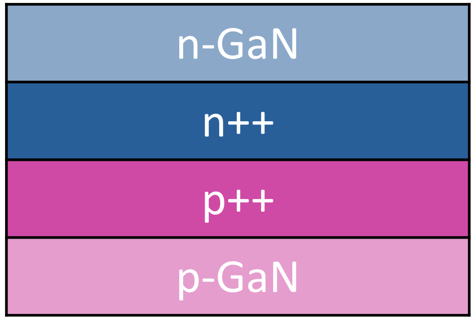
As-Grown buried RPCVD p-GaN

RPCVD p-GaN is Active As-Grown even when buried, **requiring no post-growth activation steps**

SHARP Mg DOPING PROFILE FOR ACTIVE AS-GROWN BURIED p-GaN

RPCVD TUNNEL JUNCTION SIMS





Mg turn-off for RPCVD TJ displays sharp profile

22 nm for initial reduction of Mg atomic concentration $1.0x10^{20} – 1.0x10^{19}$ cm^{-3}

Average of 26 nm / decade for 3 decades of Mg atomic concentrations

REQUIREMENTS FOR A LOW-LOSS TJLD

- GaN LDs suffer from optical and resistive loss in the Mg-containing layers
- Proposed solution to insert a TJ to replace these p-type layers with n-type layers
- TJ structure requires very high doping in the p++ and n++ layers and sharp doping profiles
- Identified RPCVD as having all the critical features to achieve this
- Greatest benefit when TJ is placed close to the active region

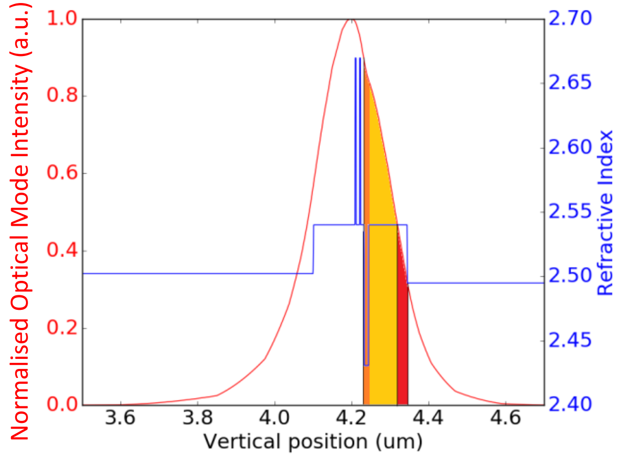
Can a TJ be designed and positioned so as to reduce the optical loss in the LD while still displaying low resistance?

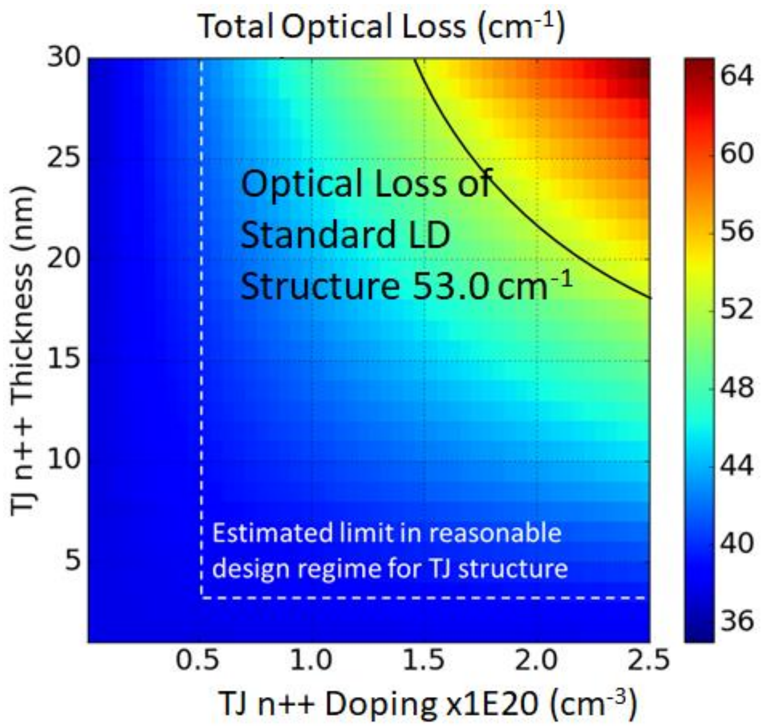
SIMULATION OF THE OPTICAL LOSS IN TJLDs

RPCVD TJLD Structure

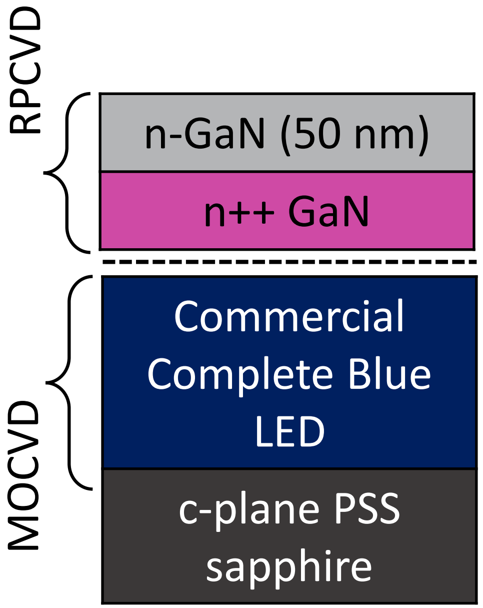
Layer	Thickness (nm)	Doping (cm^{-3})	Composition	Absorption Coefficient (cm^{-1})
n++ contact	20	1.5E20	GaN	375
n-AlGaN cladding	500	5.0E18	$Al_{0.08}Ga_{0.92}N$	125
n++	30	2.5E20	GaN	627.5
p++	10	1.0E20	GaN	250
p-WG	60	2.0E19	GaN	50
EBL	12	1.5E20	$Al_{0.2}Ga_{0.8}N$	375
2x InGaN/GaN MQW	2.7 / 9.0	-5.0E16	$In_{0.11}Ga_{0.89}N$ / GaN	12
n-WG	100	-2.0E17	GaN	12
n-AlGaN cladding	1000	-3.0E18	$Al_{0.067}Ga_{0.933}N$	12

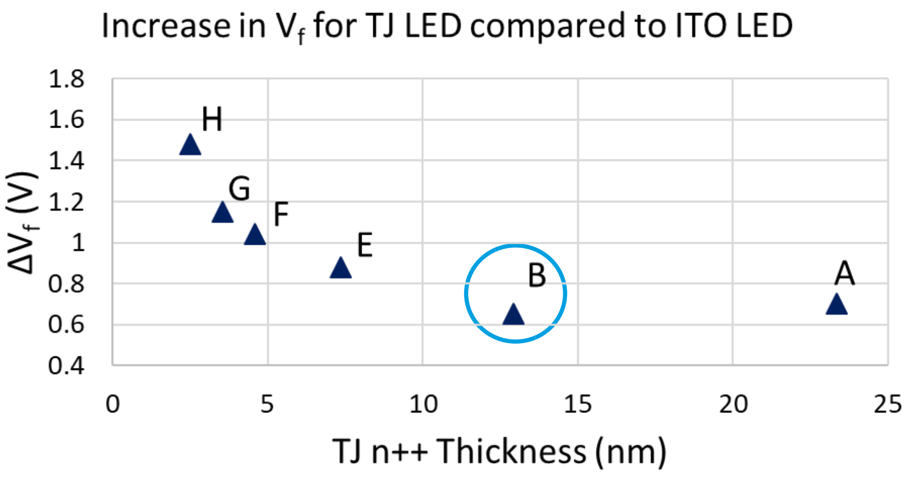
Simulation of optical mode and refractive index profile of TJLD

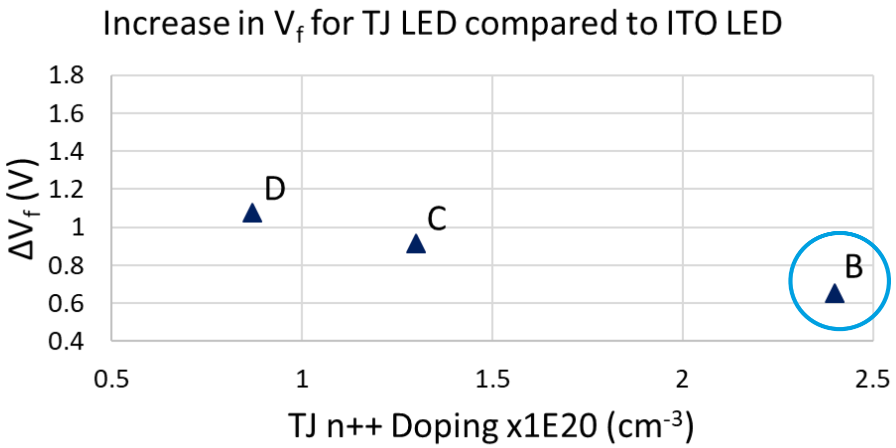


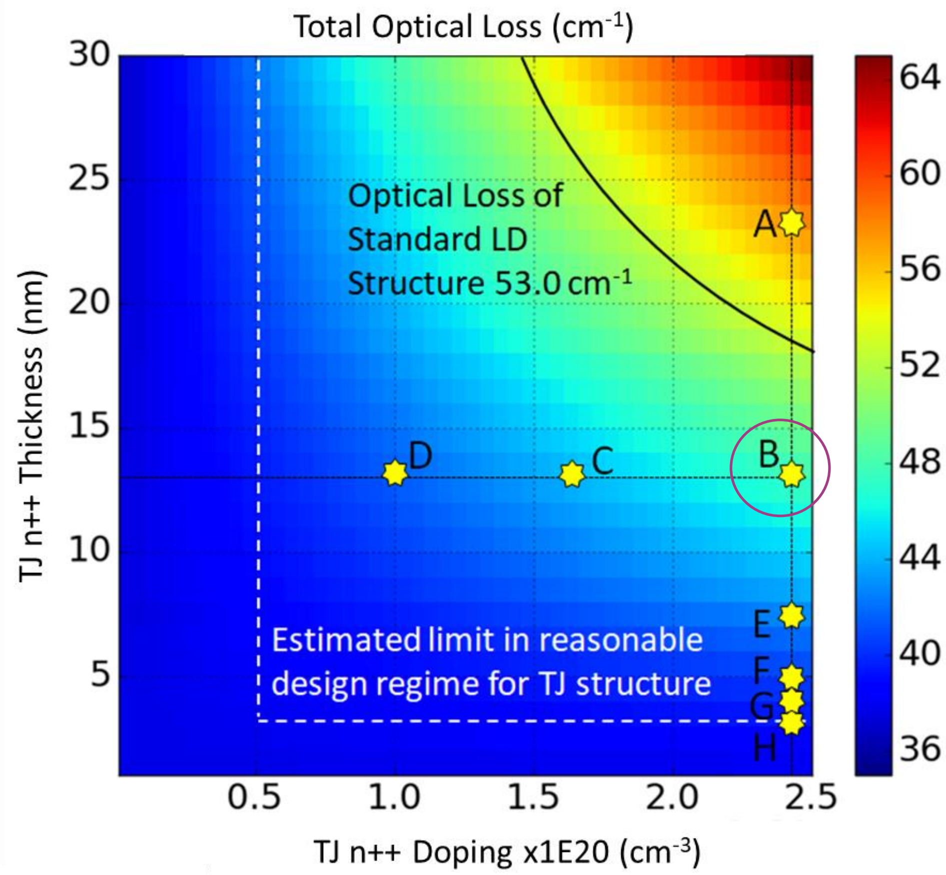


RPCVD TUNNEL JUNCTIONS FOR LOW LOSS TJLDs









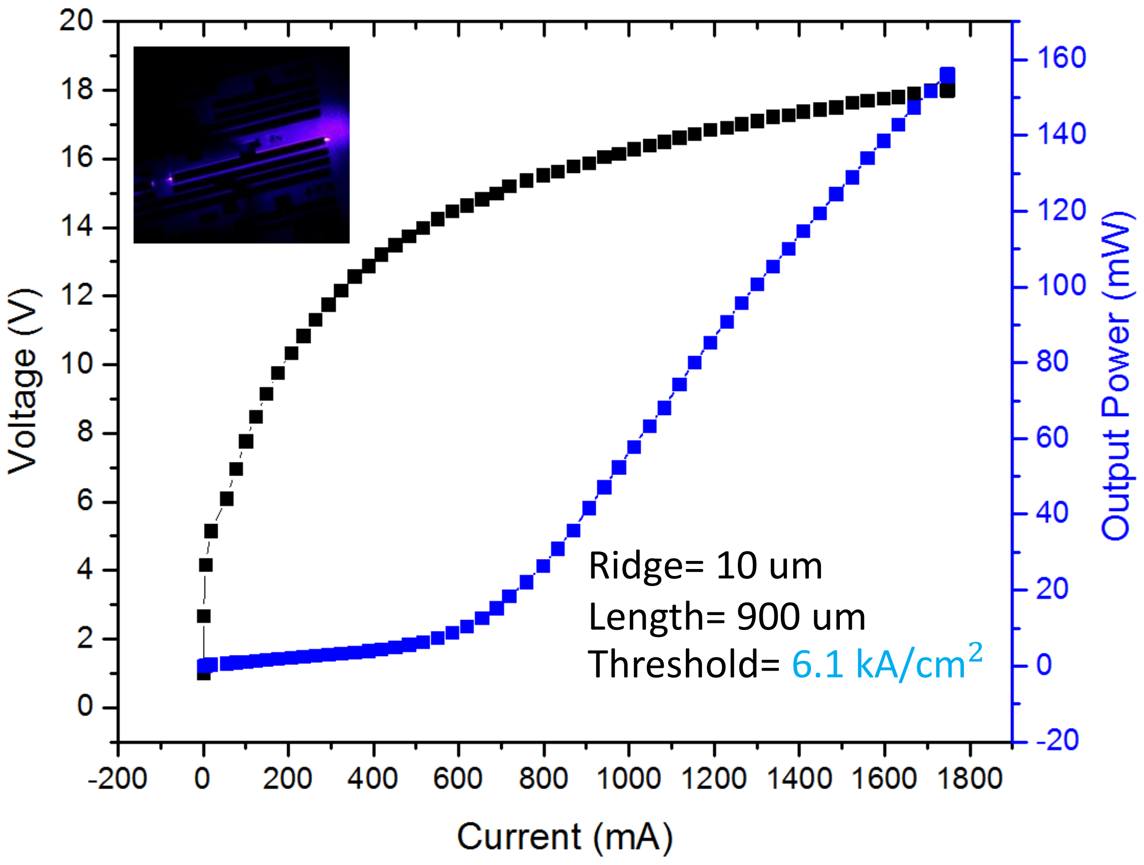
MOCVD 405 nm GaN-BASED LD ON SAPPHIRE

MOCVD Standard LD Structure

MOCVD

p++ cap	10
p-GaN	40
p-$Al_{0.084}Ga_{0.916}N$	460
p-GaN	105
$Al_{0.2}Ga_{0.8}N$	12
$In_{0.11}Ga_{0.89}N$ / GaN	(3.0/6.5) x3
n-GaN	110
n-$Al_{0.068}Ga_{0.932}N$	1500
nGaN	2800
u-GaN	3900
Sapphire	

LIV MOCVD LD on Sapphire



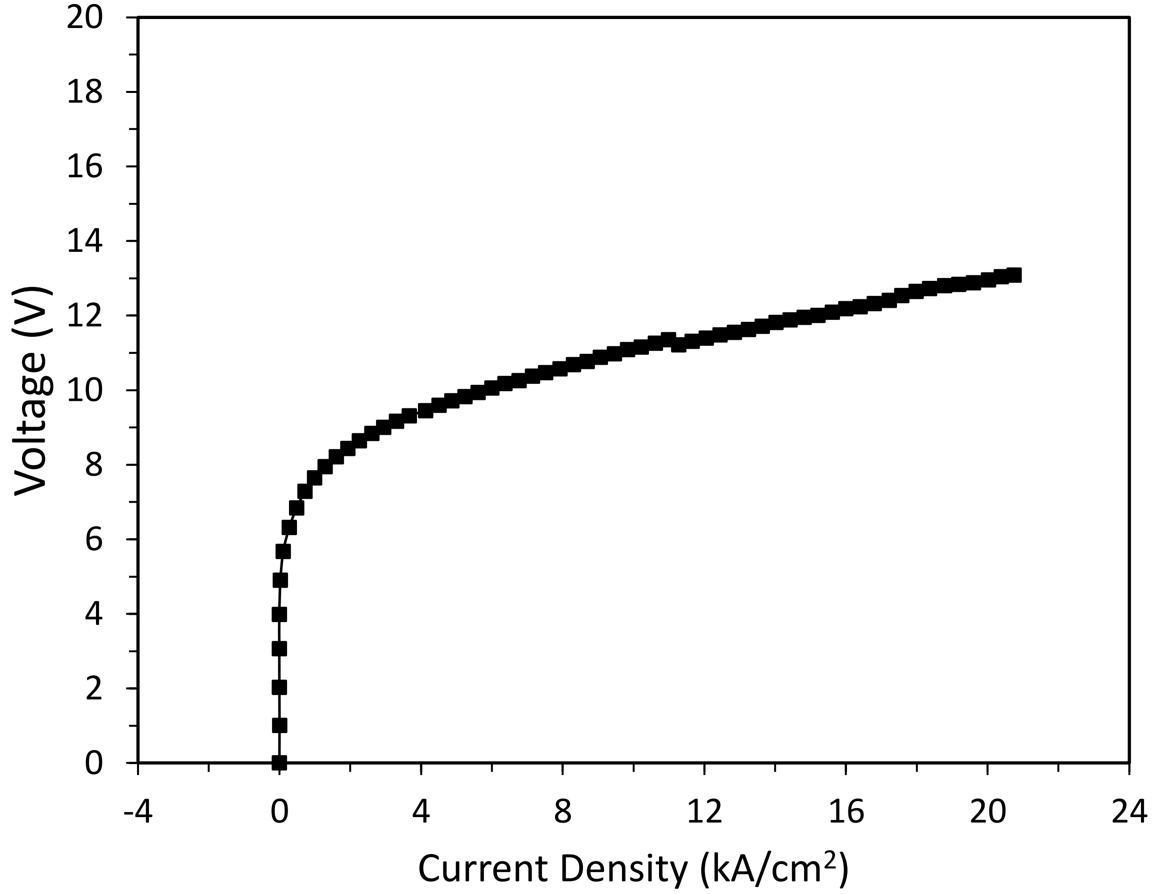
HYBRID MOCVD/RPCVD TUNNEL JUNCTION LASER DIODE

RPCVD TJLD Structure

RPCVD (n-GaN, n-$Al_{0.087}Ga_{0.913}N$, n++ GaN); TJ (n++ GaN, p++ GaN); MOCVD (p++ GaN through n-GaN 300)

Layer	Thickness (nm)
n-GaN	20
n-$Al_{0.087}Ga_{0.913}N$	500
n++ GaN	30
p++ GaN	10
p-GaN	100
$Al_{0.2}Ga_{0.8}N$	12
$In_{0.11}Ga_{0.89}N$ / GaN	(2.7/9.0) x2
n-GaN	120
n-$Al_{0.067}Ga_{0.933}N$	1000
n-GaN	300
FS GaN	

IV of RPCVD TJLD on FS GaN



SUMMARY AND FUTURE WORK

- GaN LDs suffer from optical and resistive loss in the Mg-containing layers
- Proposed solution to insert a TJ to replace these p-type layers with n-type layers
- Introduced RPCVD as a highly appropriate growth technology for realising these devices
- Demonstrated that optimised RPCVD TJs structures will not increase optical loss in the TJLD
- Preliminary MOCVD LD and TJLD Data presented

FUTURE WORK

- *Complete fabrication and testing of latest MOCVD LDs and Hybrid MOCVD/RPCVD TJLDs*
- *Optimise the MOCVD base LD process*
- *Refine the TJLD structure for improved LD performance*

THANK YOU

Dr Josh Brown
BluGlass Limited (ASX:BLG)
jbrown@bluglass.com.au

www.bluglass.com.au