07 February 2019

BLUGLASS PRESENTS LATEST RPCVD DATA AND TUNNEL JUNCTION BREAKTHROUGH AT PHOTONICS WEST CONFERENCE

Australian technology innovator, BluGlass Limited (ASX:BLG) has today presented its latest ***remote plasma chemical vapour deposition (RPCVD)*** technical data, at the Photonics West Conference in San Francisco, the leading global event for the photonics and laser industries. The presentation includes data on the Company's recent breakthrough development of RPCVD grown tunnel junctions for LED applications.

BluGlass Chief Technology Officer, Dr. Ian Mann is an invited speaker at the conference, and presented a paper titled '***RPCVD of Group III Nitride Tunnel Junctions for LED Applications'***. Dr. Mann outlined the technical detail and competitive advantages of the Company's patented RPCVD technology for the manufacture of GaN-based tunnel junctions in cascade LEDs. RPCVD enabled cascade LEDs are a promising solution that could address the significant industry challenge of LED efficiency droop.

BluGlass is commercialising a novel semiconductor manufacturing process called RPCVD - for the manufacture of high-performance LEDs, microLEDs and power electronics- that offers several potential benefits to manufacturers, including higher performing, lower cost and smaller devices.

In December 2018, the Company announced that it has successfully demonstrated functioning tunnel junctions, capitalising on the unique low temperature advantages of RPCVD. Tunnel junctions are a key building block for cascade LEDs.

A cascade LED is where two or more LEDs are grown in a continuous vertical stack using a tunnel junction to interconnect multiple LEDs in a single chip. This is highly desirable as it could prevent the fundamental challenge of 'efficiency droop' in high performance LEDs, by decreasing the required electric current while increasing the light-output. Cascade LEDs are expected to enable smaller, cheaper and higher performing LEDs – the three key interest areas of the LED industry. To date, functioning tunnel junctions, and therefore cascade LEDs have been prohibitively difficult to produce.

BluGlass Managing Director, Giles Bourne, said, "We are very pleased to be presenting this breakthrough development of our technology with the industry today. These exciting results help validate the strong commercial potential of our RPCVD technology to solve a number of the manufacturing challenges associated with the industry's incumbent processes.

"Importantly this allows us to further discussions with a range of potential high-value partners in the LED and other semiconductor market segments, as we seek to capitalise on the broader commercial applications for our technology."

There is significant interest in the potential of cascade LEDs and tunnel junctions, as efficiency droop is a well-known problem associated with high performance GaN-based LEDs. It is a fundamental property of LEDs where the efficiency of the light-output drops as the driving current increases, which means that the majority of today's high-powered LEDs are being operated outside of their peak efficiency.

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RPCVD grown tunnel junctions could be commercially compelling for all high-performance nitride devices, including for high value applications such as LEDs for automotive lighting, UV LEDs for water purification, high power laser diodes for industrial machining applications and high efficiency multi-junction concentrated solar cells.

The global LED market is predicted to reach US $96B by 2024, with the high-brightness automotive segment (a potential first adopter of cascade LEDs due to strict performance and size requirements) expected to represent $22B by 2024, capturing ~23% of the total market.

The RPCVD process can produce these critical enabling tunnel junctions in the LED device by capitalising on its inherent competitive advantages. RPCVD operates at hundreds of degrees cooler than the incumbent technology and replaces expensive and toxic ammonia with an inert nitrogen plasma. It is also able to achieve the required activation needed for a working tunnel junction during growth. The industry incumbent process, metal organic chemical vapour deposition (MOCVD) relies on complicated and time-consuming ex-situ processing to achieve the required activation. This unique ***'as-grown and activated p-GaN'*** (or AAG) technology is a fundamental advantage of RPCVD.

Since notifying the market in December of our tunnel junction capabilities, BluGlass has received strong industry interest and looks forward to progressing those discussions with the technical details provided today.

A copy of Dr. Mann's technical presentation is included below or available to download from our website www.bluglass.com.au

BluGlass is also exhibiting at Photonics West, visit us at booth 4377.

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 light emitting diodes (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. BluGlass was spun off from Macquarie University in 2005 and listed in 2006.

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Remote Plasma Chemical Vapour Deposition (RPCVD) of Group III-Nitrides for LED Tunnel Junction Applications

Dr Ian Mann

CTO/COO - BluGlass Limited

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2019

Feb 6th, 2019

SPIE Photonics West OPTO 2019 – San Francisco

FORWARD LOOKING STATEMENTS

This document has been prepared by BluGlass Limited to provide readers with a summary of the Company and the Company's technology

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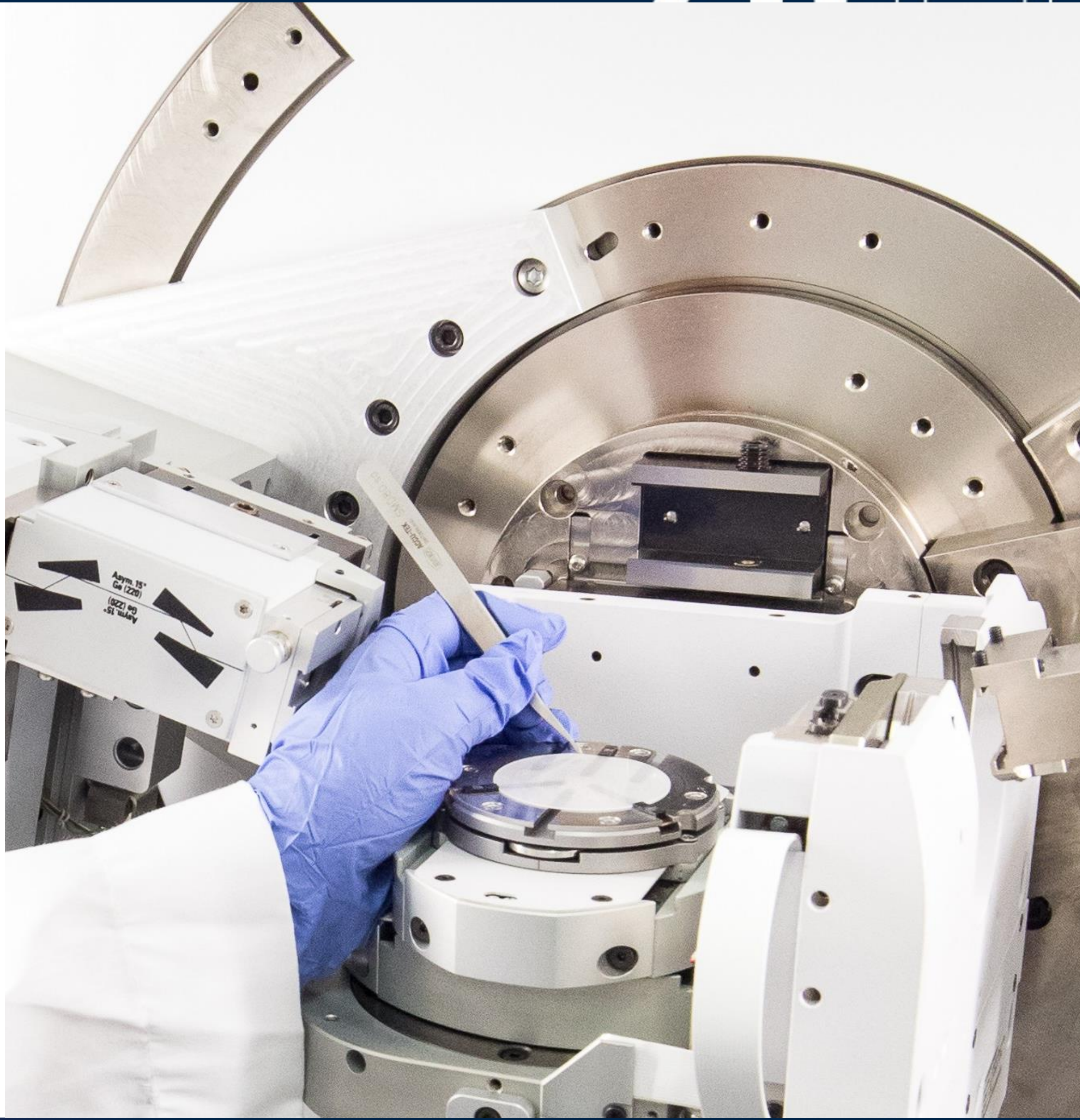
OUTLINE

- BluGlass Limited Overview
- Introduction to RPCVD
- RPCVD GaN Growth
- RPCVD p-n Junctions and MQWs
- RPCVD for Tunnel Junctions
- Future work: Cascade LEDs
- Summary



ACKNOWLEDGEMENTS

BLUGLASS LIMITED

- S. Barik, D. Liu, J. D. Brown, M. Wintrebert-Fouquet, A. J. Fernandes, P. P. -T. Chen, Q. Gao, V. Chan
- D. Timoney, S Chiappa, S. O’Farrell, R. Connor, A. Burgess, I. Cruz

MOCVD SOLUTIONS LTD, UK

- Laurence Considine

BLUGLASS LIMITED CORPORATE OVERVIEW

2019

COMPANY

2006

Established via a spin off from Macquarie University

ASX:BLG

Listed on the Australian Stock Exchange

AU$125.4M

Market Cap as at 1 Feb. 2019

CAPABILITIES & SERVICES

DEVELOPING RPCVD

Conducting applied research and commercialisation of RPCVD for LED, microLED and HEMT applications

63 PATENTS

Internationally granted patents in key semiconductor jurisdictions including US, Europe, Japan & China

CUSTOM GaN EPI SERVICES

Offering a full suite of RPCVD and MOCVD and characterisation services

TALENT

22 STAFF

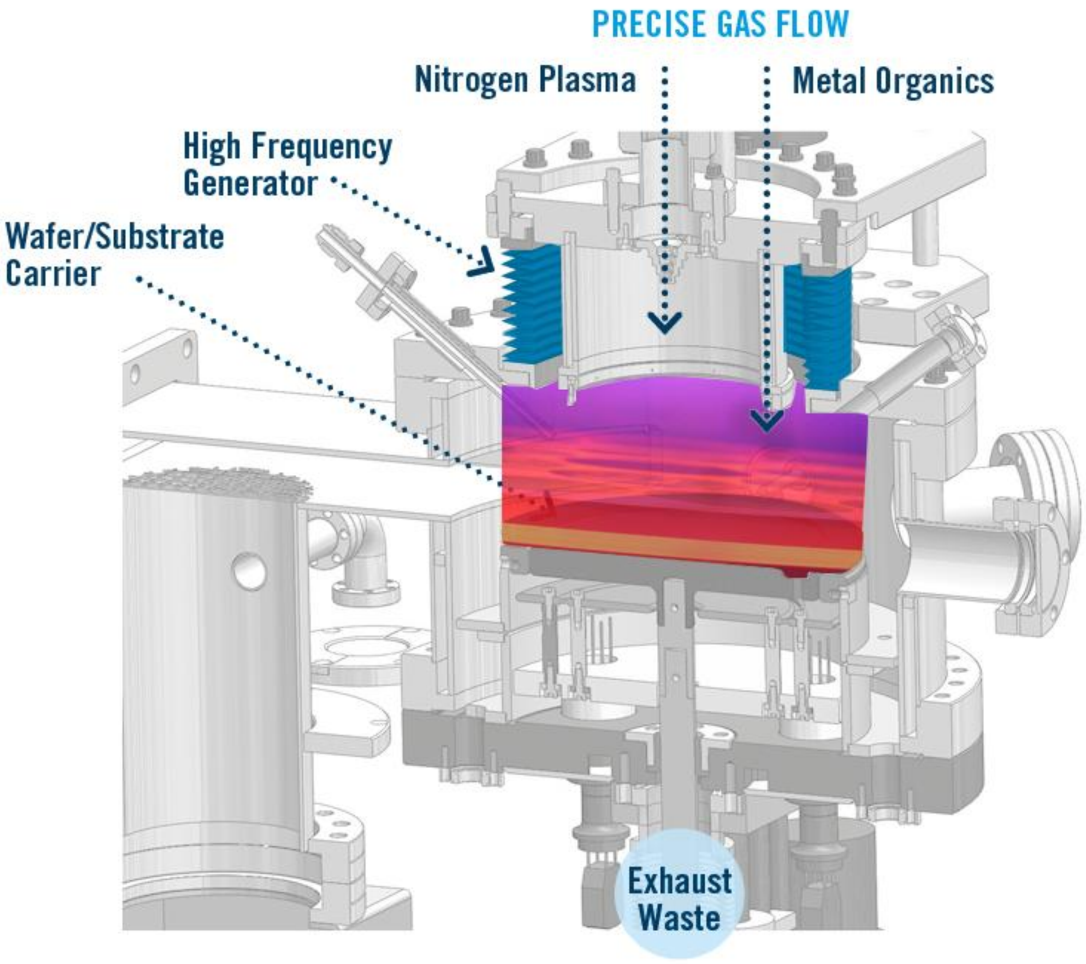
8 PhDs, Highly specialist R&D, Engineering & Commercial team

AU & US

Based in Australia with US Business Development Office

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

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



FACILITY CAPABILITY & CAPACITY IN 2019

Existing RPCVD & MOCVD Labs
(3 Prototyping Systems)

USE: *2 RPCVD system for process development*

1 MOCVD system for custom epi services and RPCVD support

OUTPUT

- IP generation
- RPCVD demonstrators
- Collaborations
- MOCVD custom epitaxial services

New Production Bay 1
(1 x RPCVD System)

USE: *RPCVD industry projects*

Support hardware and process development

FUTURE OUTPUT

- Sell RPCVD wafers and epitaxial services directly to customers

AIXTRON – BluGlass Collaboration – (RPCVD on a G4)

USE: *RPCVD scaling (6x6")*

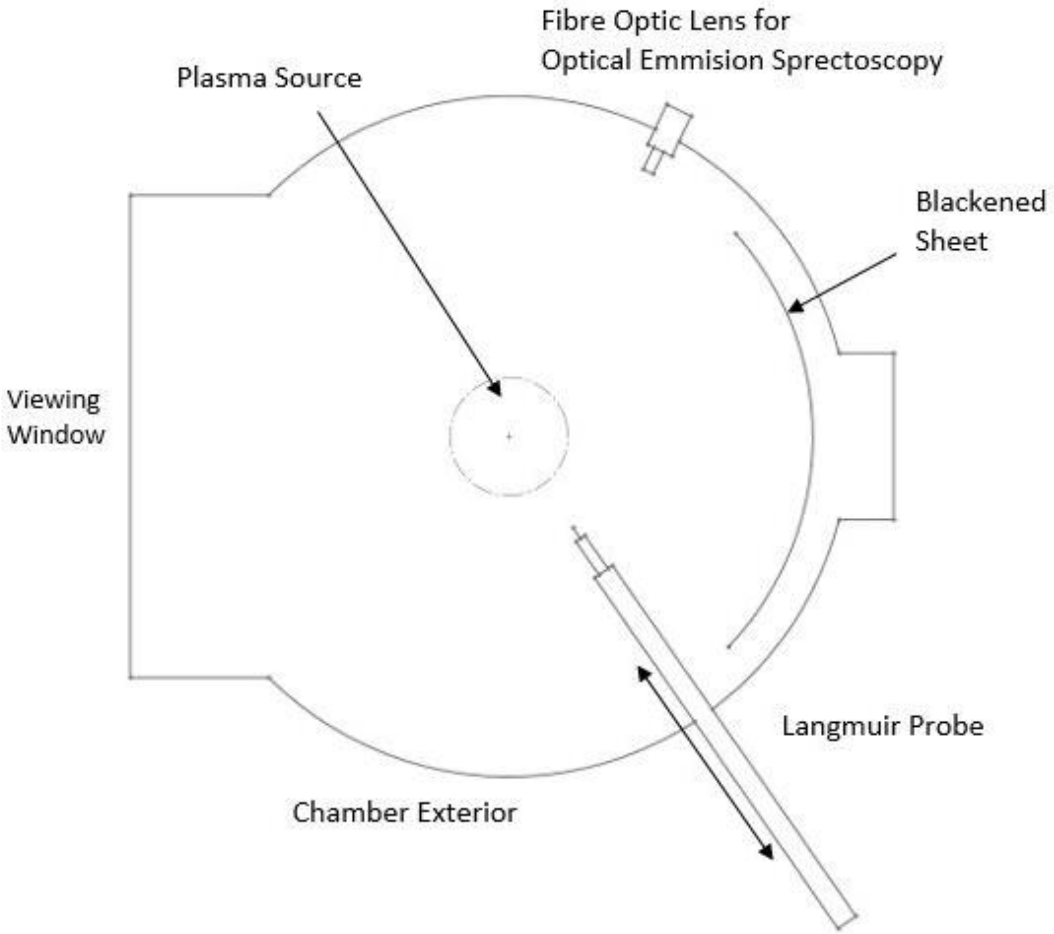
Demonstration of industry projects on production scale

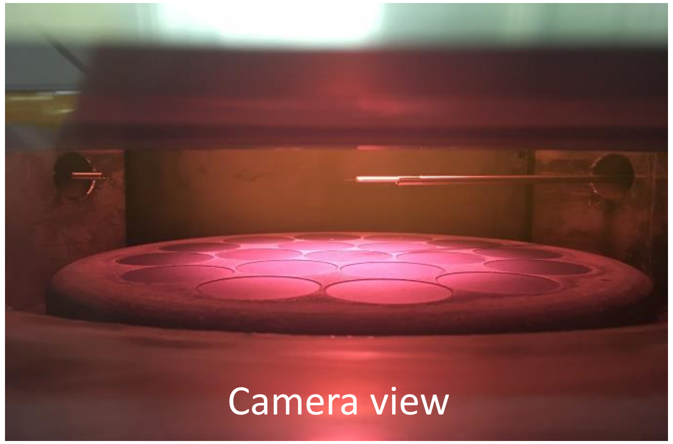
FUTURE OUTPUT

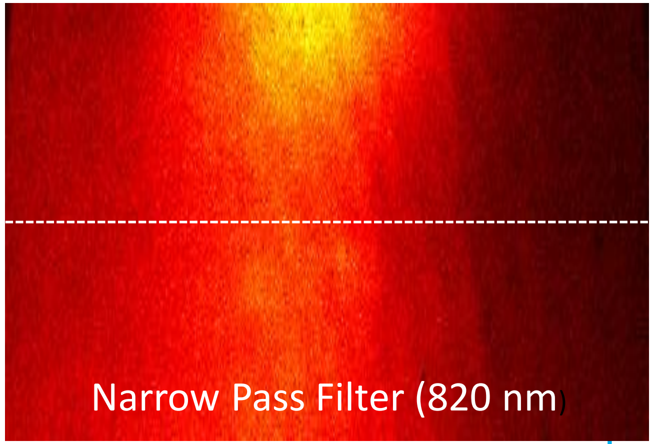
- Design, build and sell retrofit RPCVD systems directly to customers

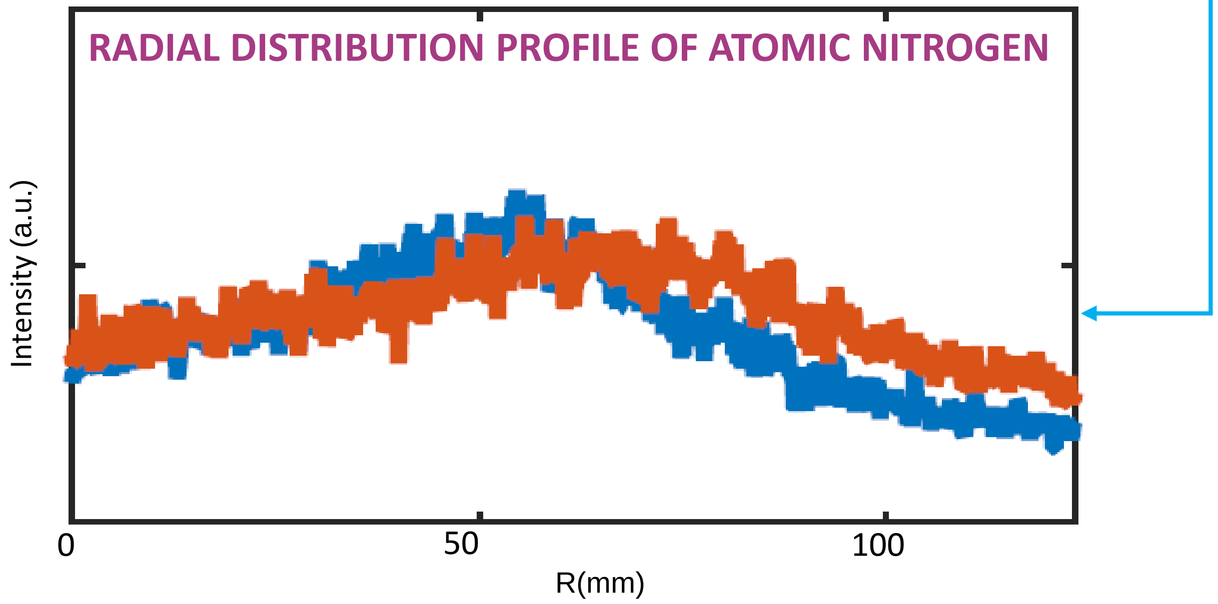
BLUGLASS DIFERENTIATION – HIGH DENISTY NITROGEN PLASMA SOURCE

PLASMA TEST RIG EXPERIMENTAL SETUP

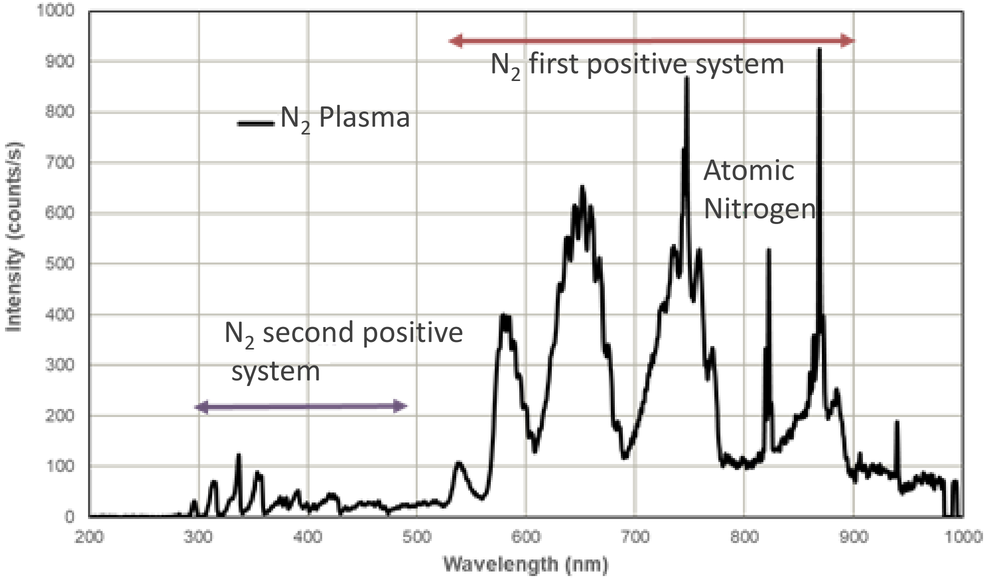


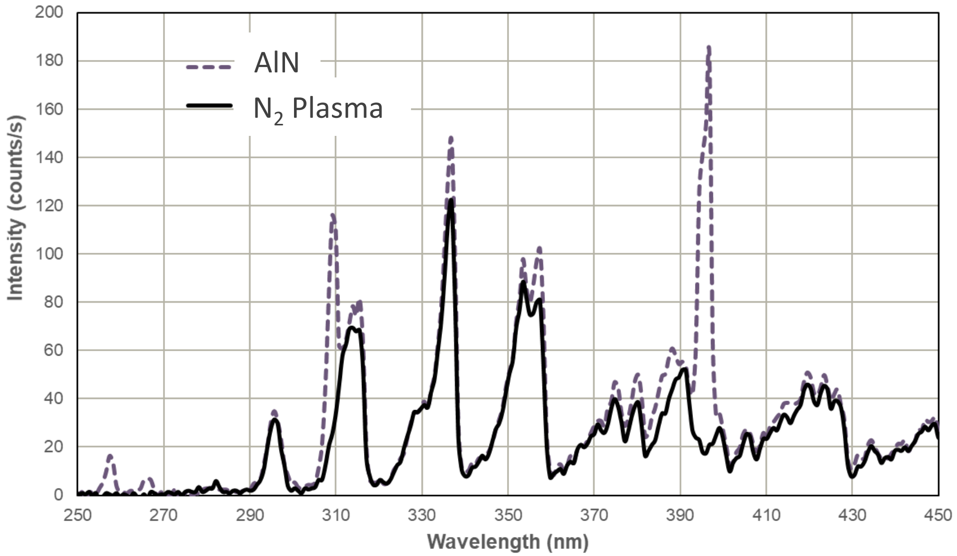


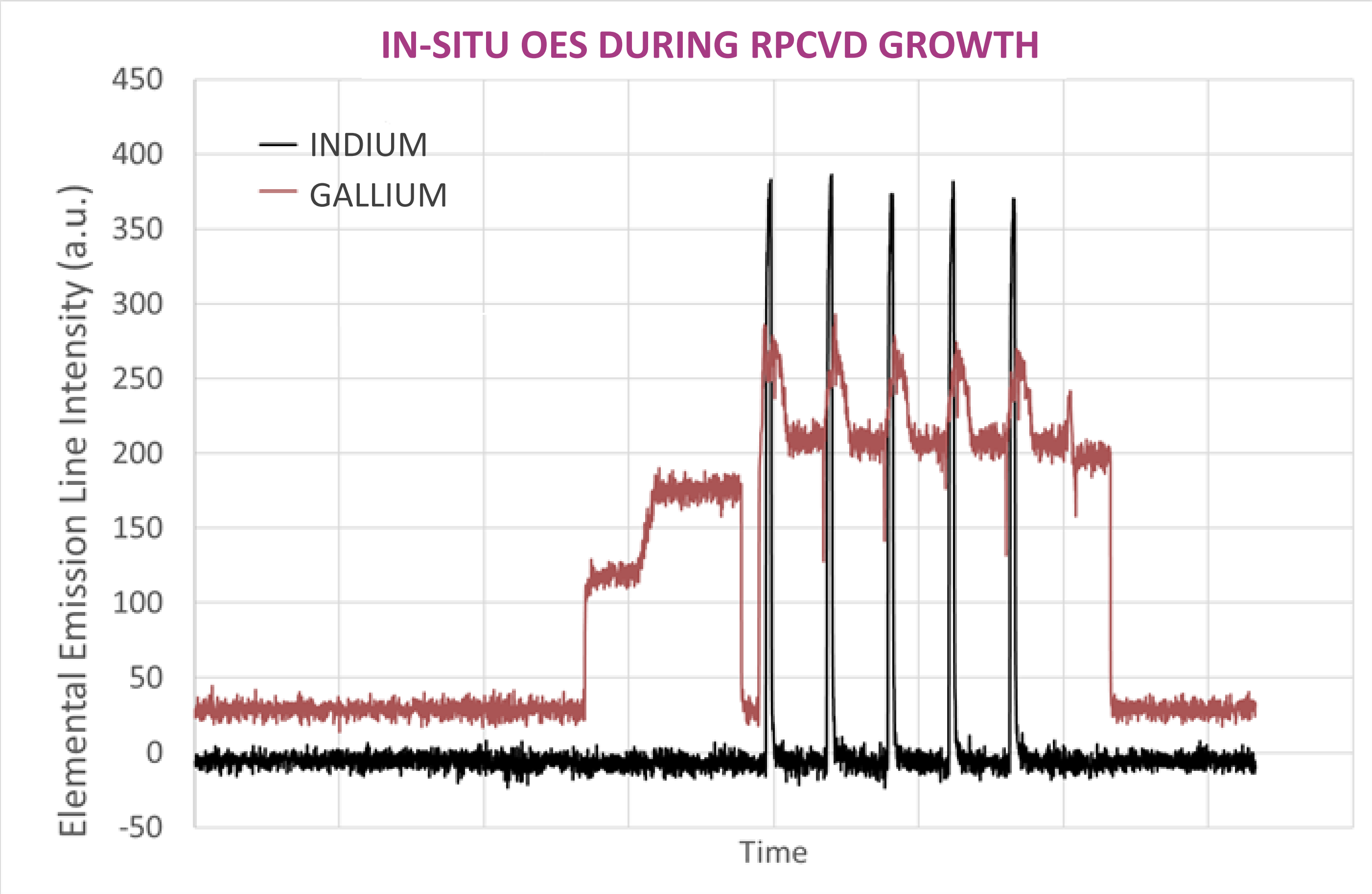




IN-SITU OPTICAL EMISSION SPECTROSCOPY FOR RPCVD



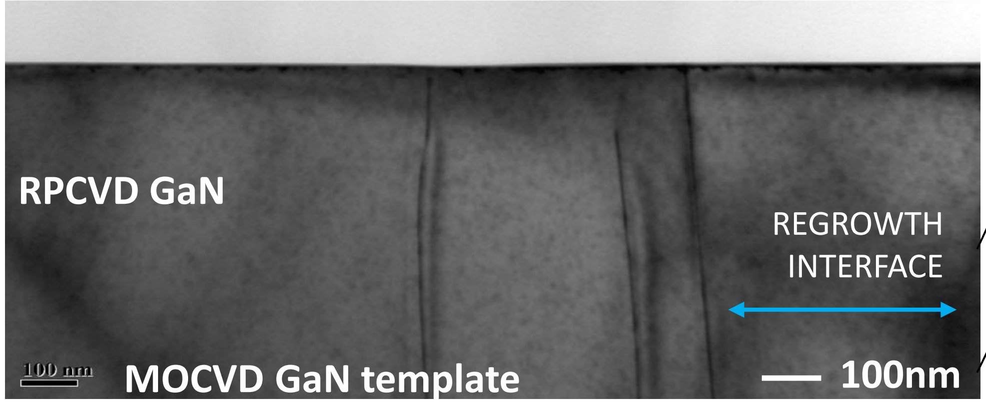




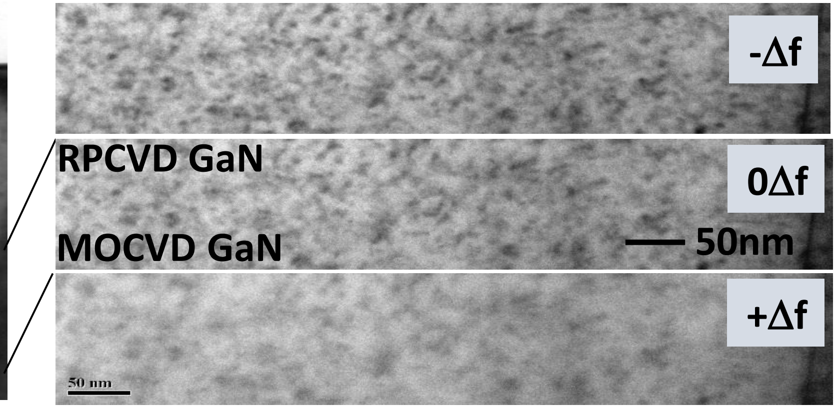
OES during growth of InGaN/GaN MQWs

RPCVD u-GaN GROWN ON MOCVD GaN TEMPLATES (ON PLANAR SAPPHIRE)

CROSS-SECTIONAL TEM: RPCVD u-GaN (TOP LAYER) ON AN MOCVD TEMPLATE

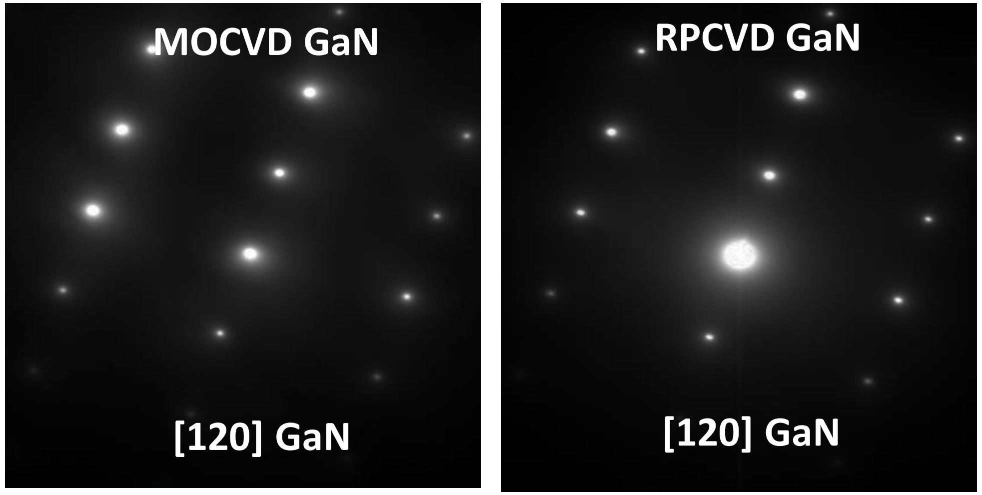


CROSS-SECTIONAL TEM: DEFOCUS IMAGES

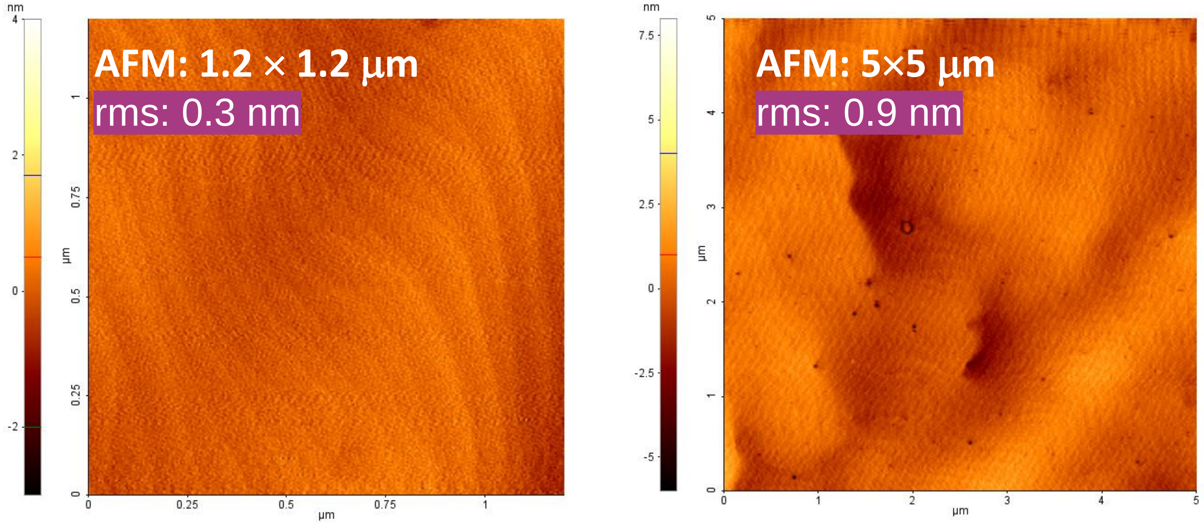


Low temperature RPCVD growth (<850 °C) produces good crystal quality

TEM DIFFRACTION PATTERNS



RPCVD u-GaN ON MOCVD TEMPLATE AFM (non-contact mode)



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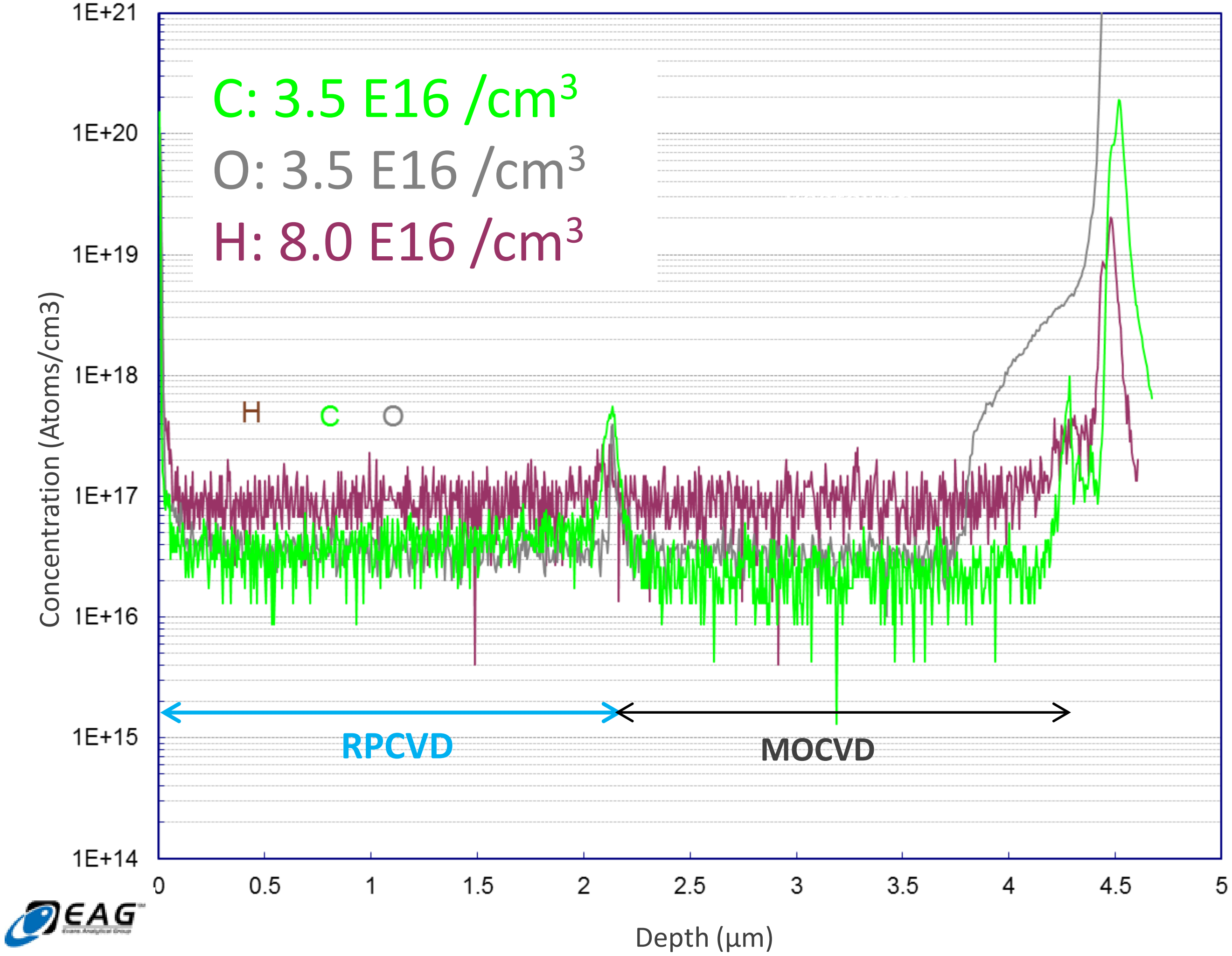
RPCVD – LOW CARBON AT LOW TEMPERATURE (ON PLANAR SAPPHIRE)

SIMS: RPCVD u-GaN ON MOCVD GaN TEMPLATE



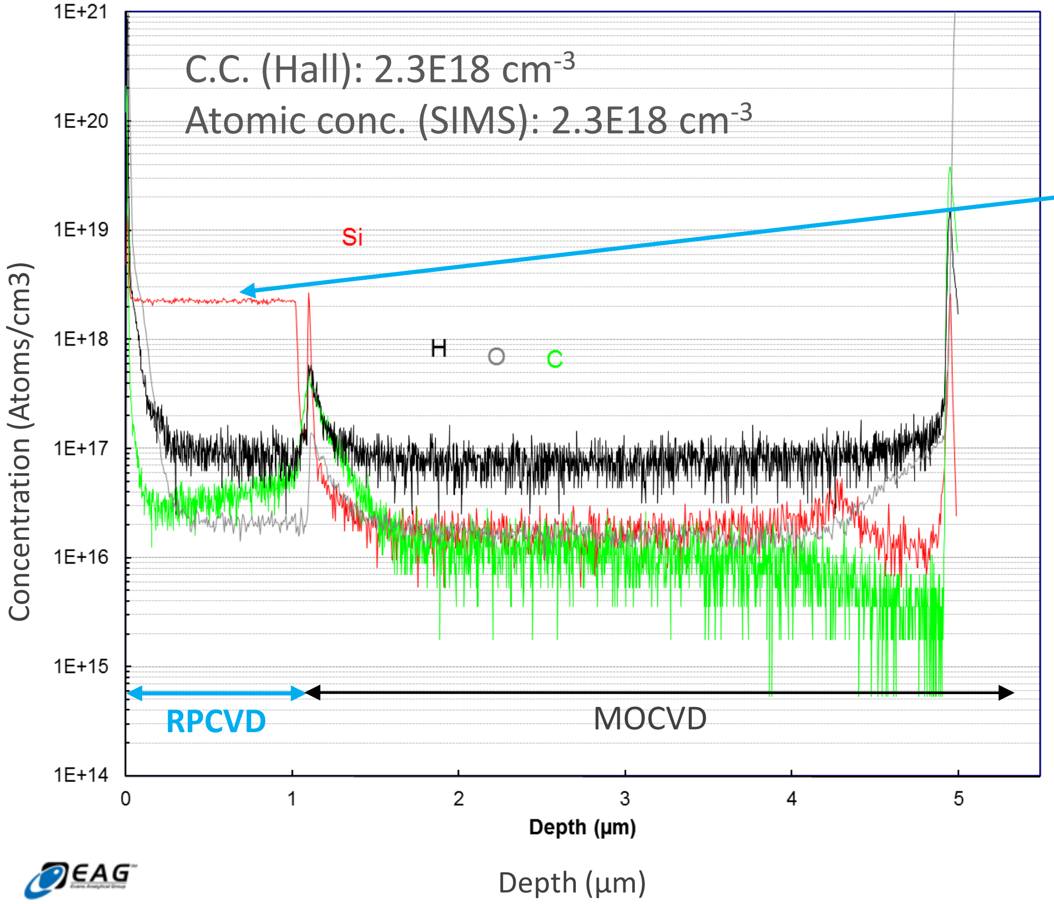
Low carbon levels with good crystal quality with low temperature growth (<850 °C)

This crystal quality with low carbon levels is unachievable by MOCVD at this growth temperature

RPCVD n-TYPE GaN (GROWN AT < 850 °C)

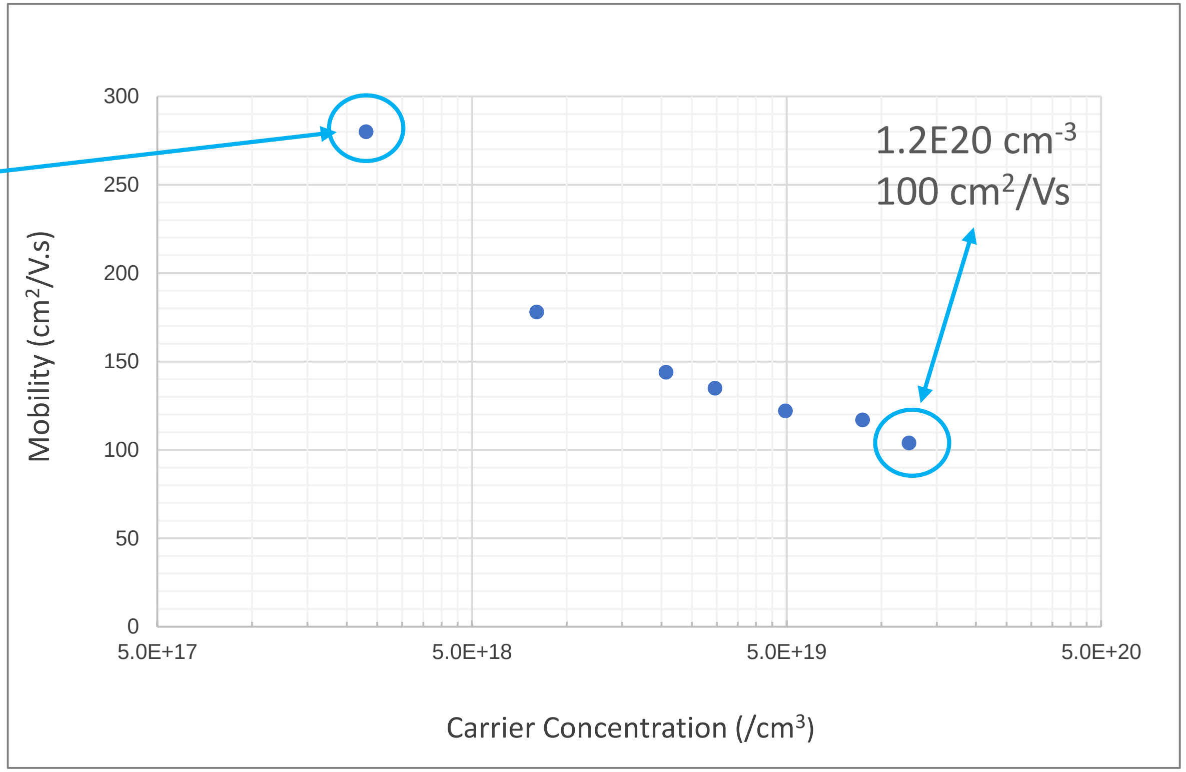
RPCVD n-GaN OVERGROWN ON AN MOCVD u-GaN TEMPLATE

RPCVD n-GaN SIMS



Depth (µm)

Hall µ VS. C.C. FOR RPCVD n-GaN

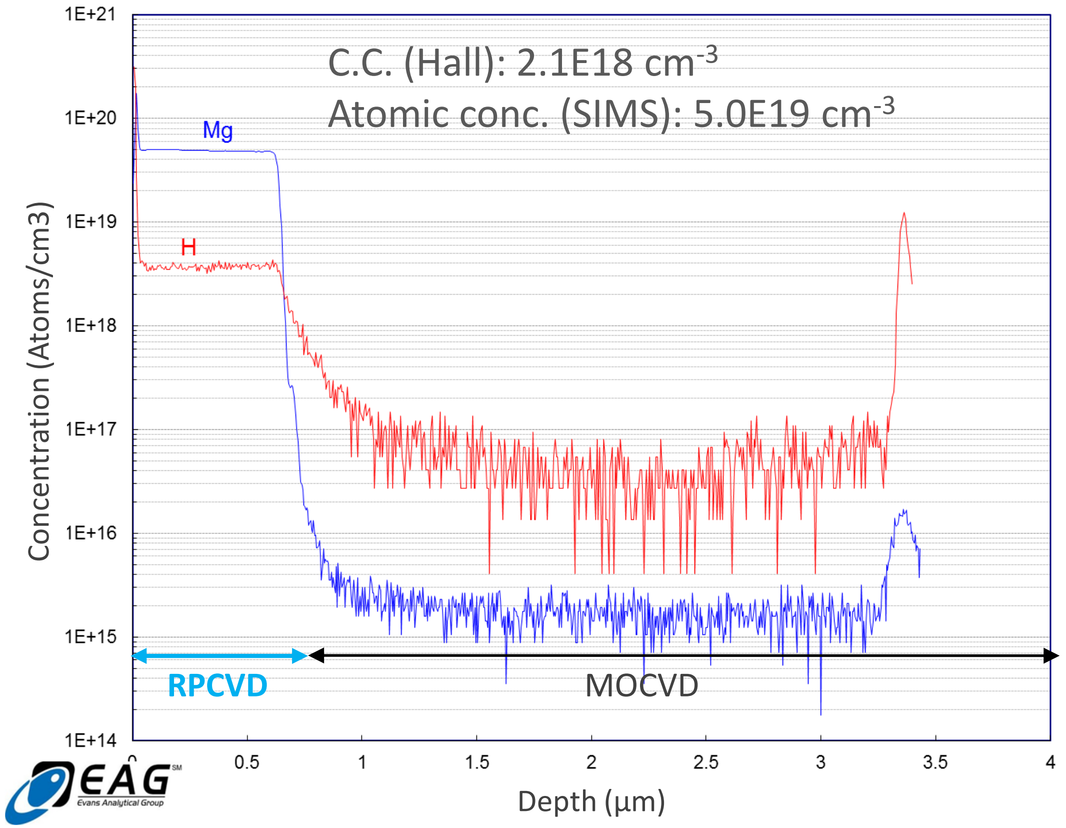


RPCVD p-TYPE GaN (GROWN AT < 850 °C)

RPCVD p-GaN OVERGROWN ON AN MOCVD u-GaN TEMPLATE

Room Temperature p-GaN Hall Measurements		
C.C. ($/cm^3$)	Mobility (cm^2/Vs)	Resistivity (Ω·cm)
2.1E18	**3.5**	**1.1**
1.4E18	5.0	0.9

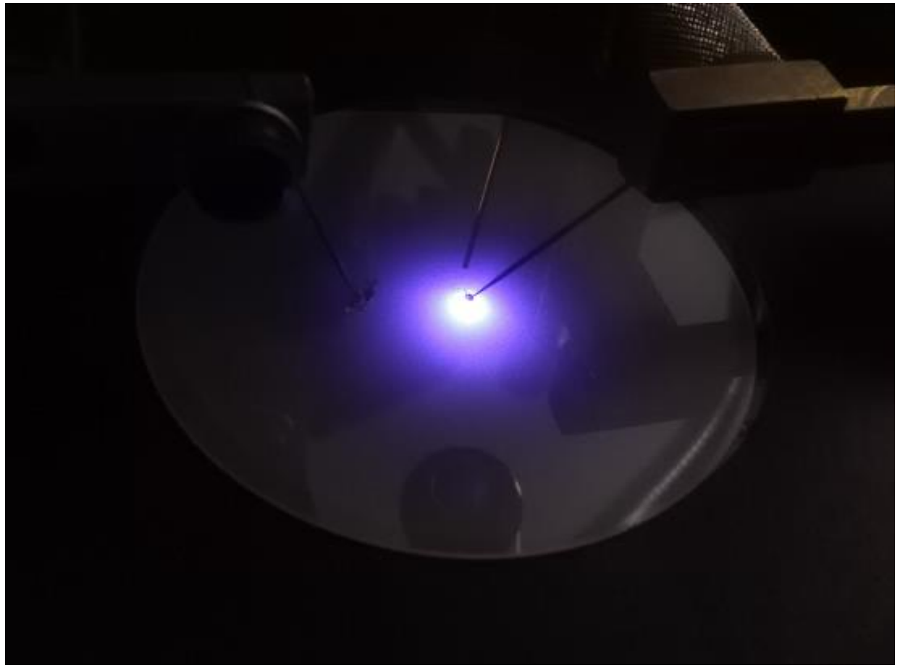
RPCVD p-GaN SIMS



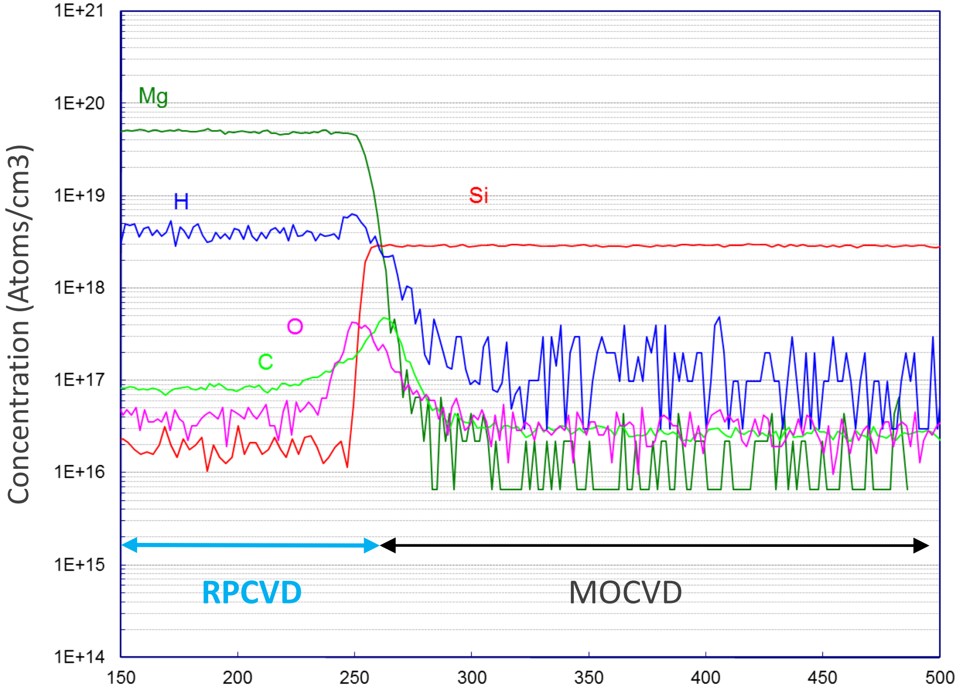
RPCVD p-n JUNCTION (GROWN AT < 850 °C)

p-n JUNCTION WITH RPCVD p-GaN OVERGROWN ON AN MOCVD n-GaN TEMPLATE

ELECTRO-LUMINESCENCE (EL) DEMONSTRATION



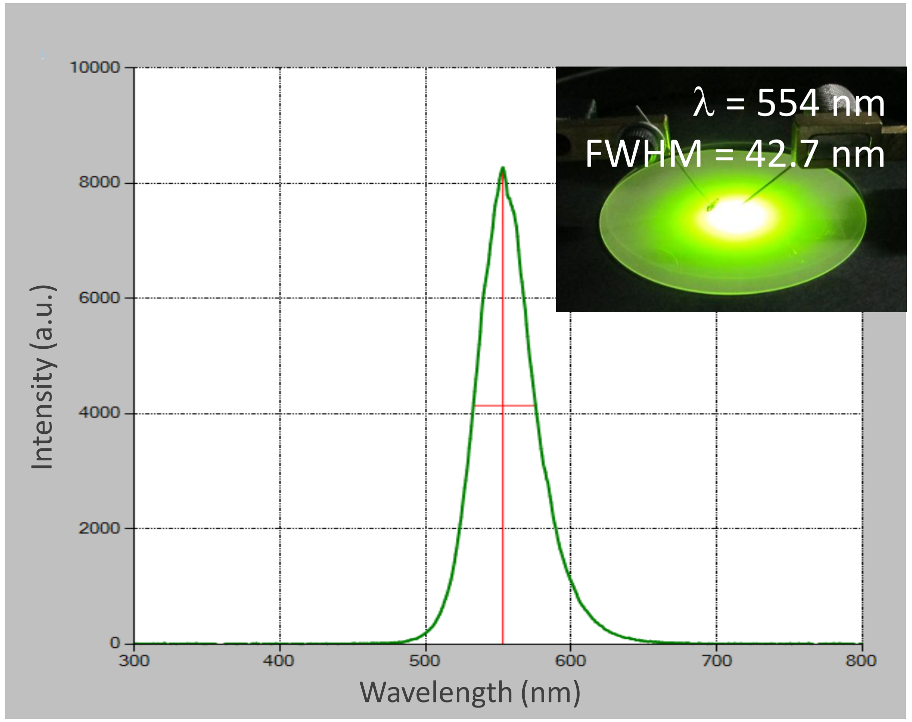
RPCVD p-n JUNCTION SIMS



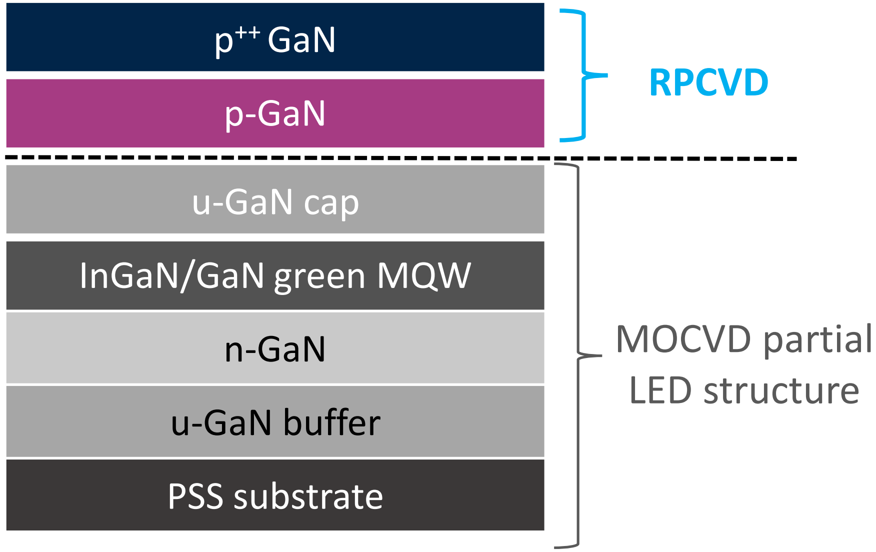
- ***Sharp Mg diffusion profile due to low temperature growth***
  - *Clean re-growth interface*

RPCVD p-GaN GROWN AT LOWER TEMPERATURE COMPARED TO MOCVD p-GaN FOR LED APPLICATIONS

EL SPECTRUM AT 200 mA

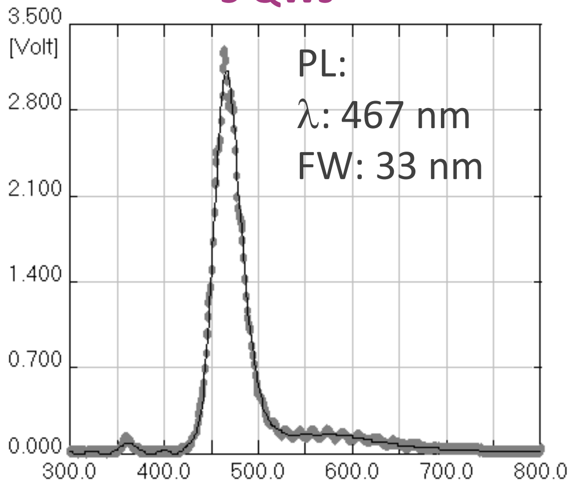


RPCVD p-GaN LED STRUCTURE

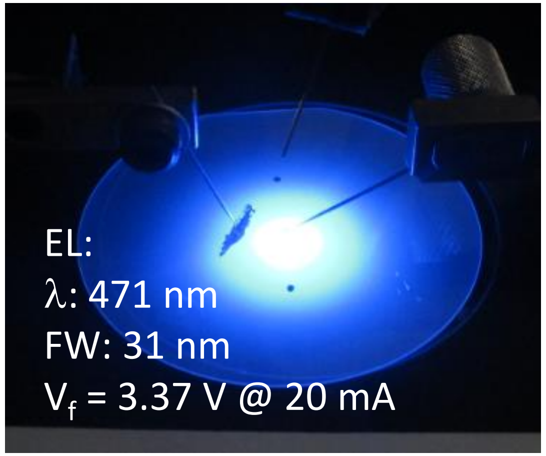


RPCVD MQWs

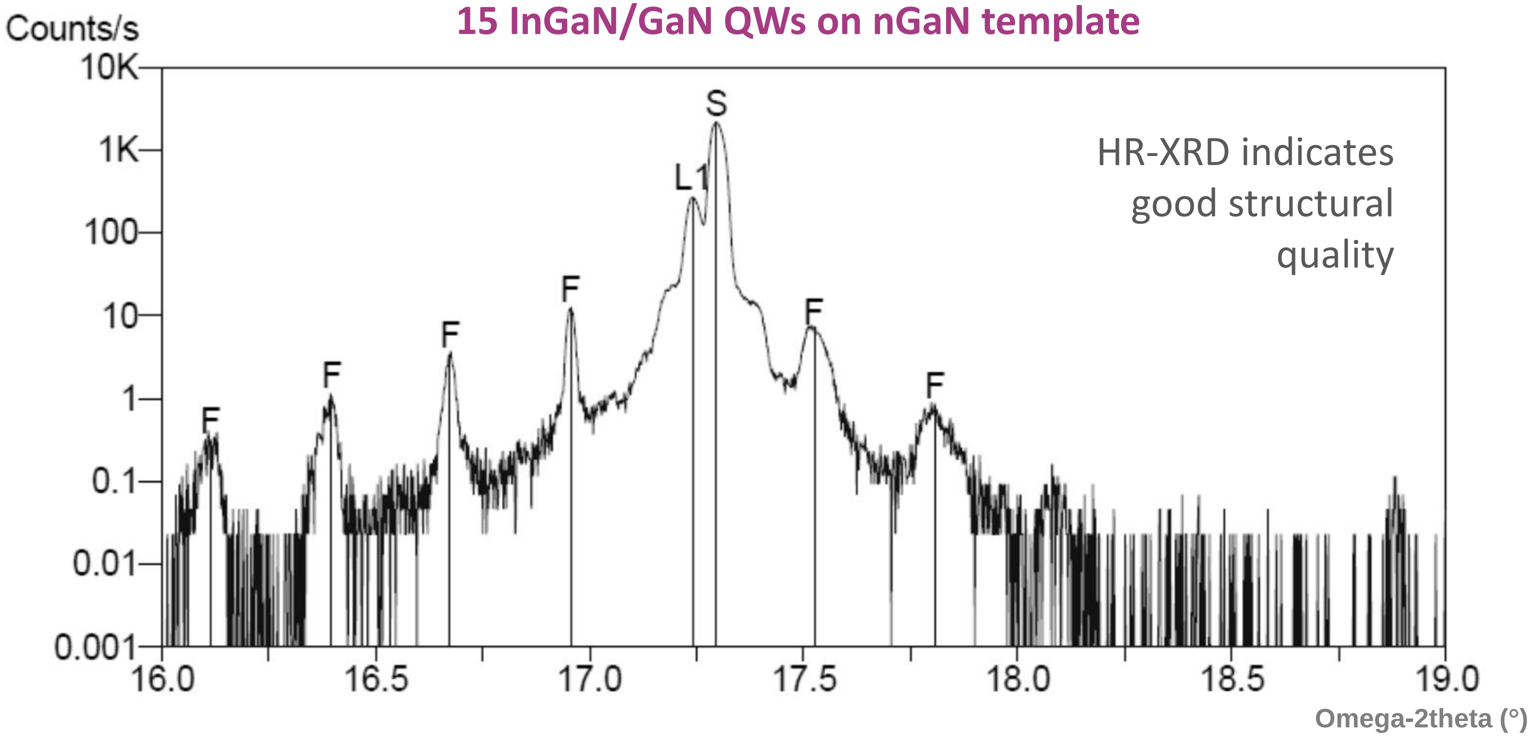
5 QWs



5 QWs



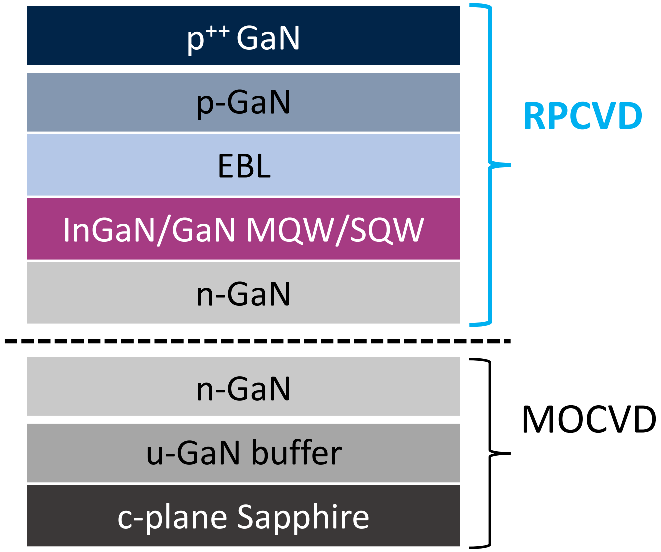
15 InGaN/GaN QWs on nGaN template

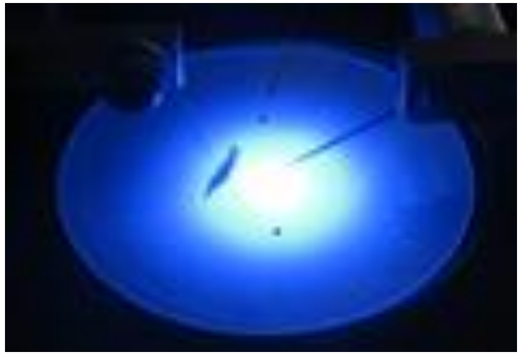


RPCVD growth of InGaN MQWs:

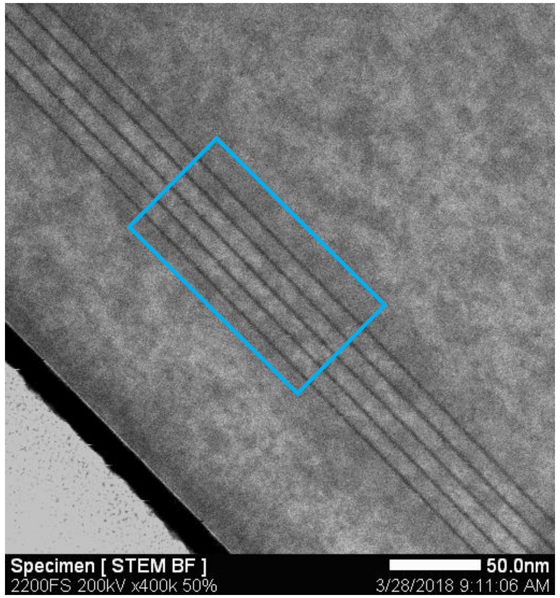
- *Low temperature*
- *Low hydrogen environment*

All RPCVD LED GROWN ON n-GaN MOCVD TEMPLATE

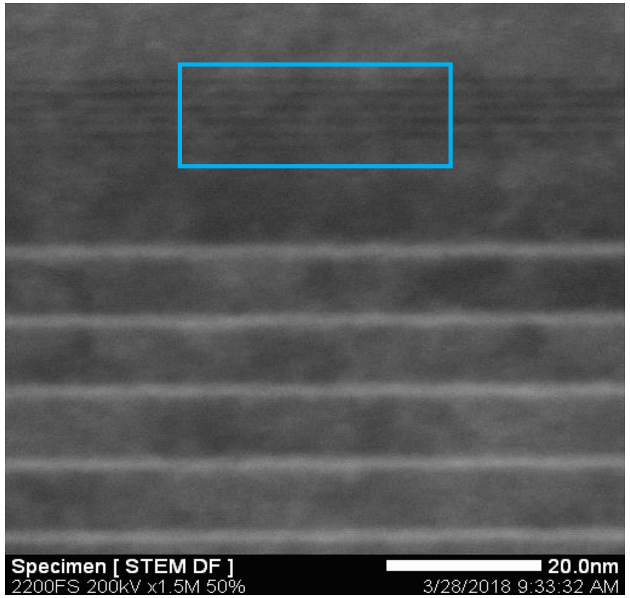




STEM BF: 5x InGaN/GaN Blue MQWs

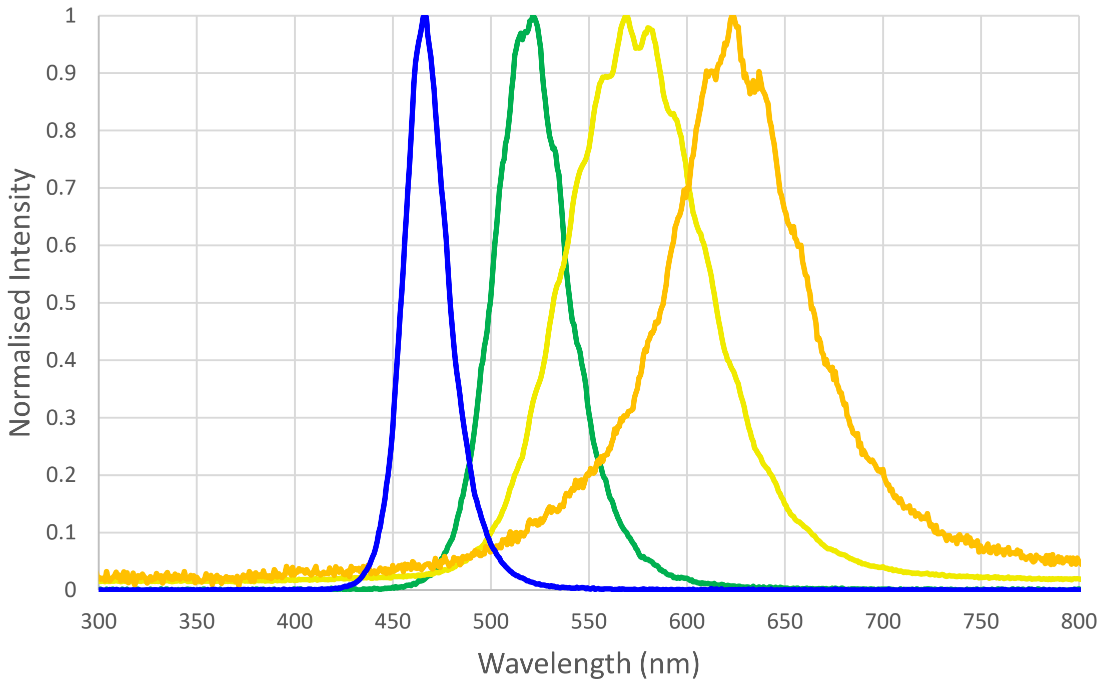


STEM DF: 5x p-AlGaN/p-GaN EBL S.L.

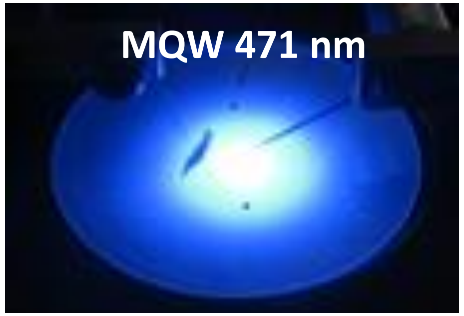


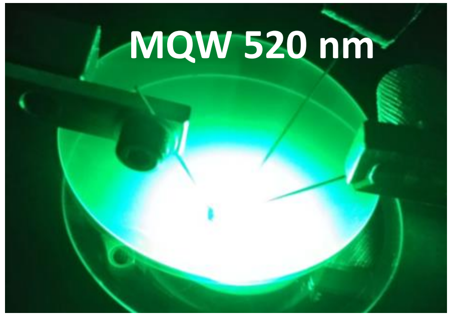
ALL RPCVD LEDS

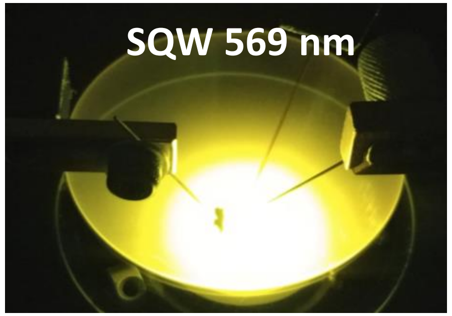
ELECTROLUMINESCENCE SPECTRA OF RPCVD LEDs

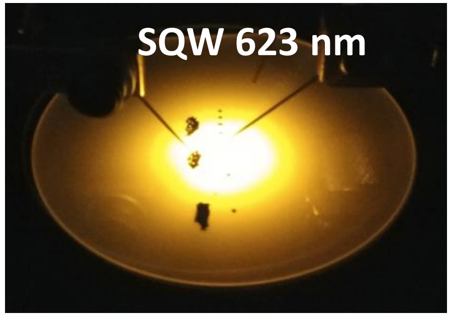


LED	Peak Wavelength (nm)	FWHM (nm)
Blue MQW	471	25
Green MQW	520	31
Yellow SQW	569	83
Amber SQW	623	82

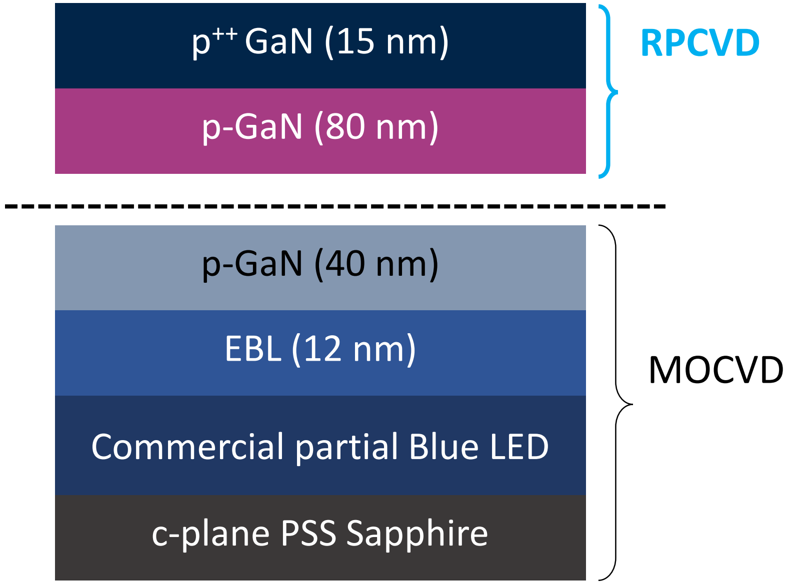


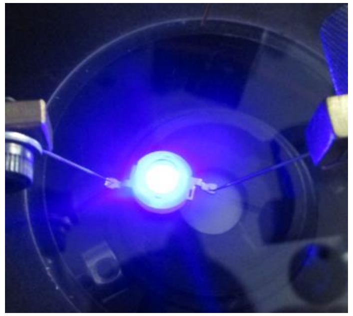




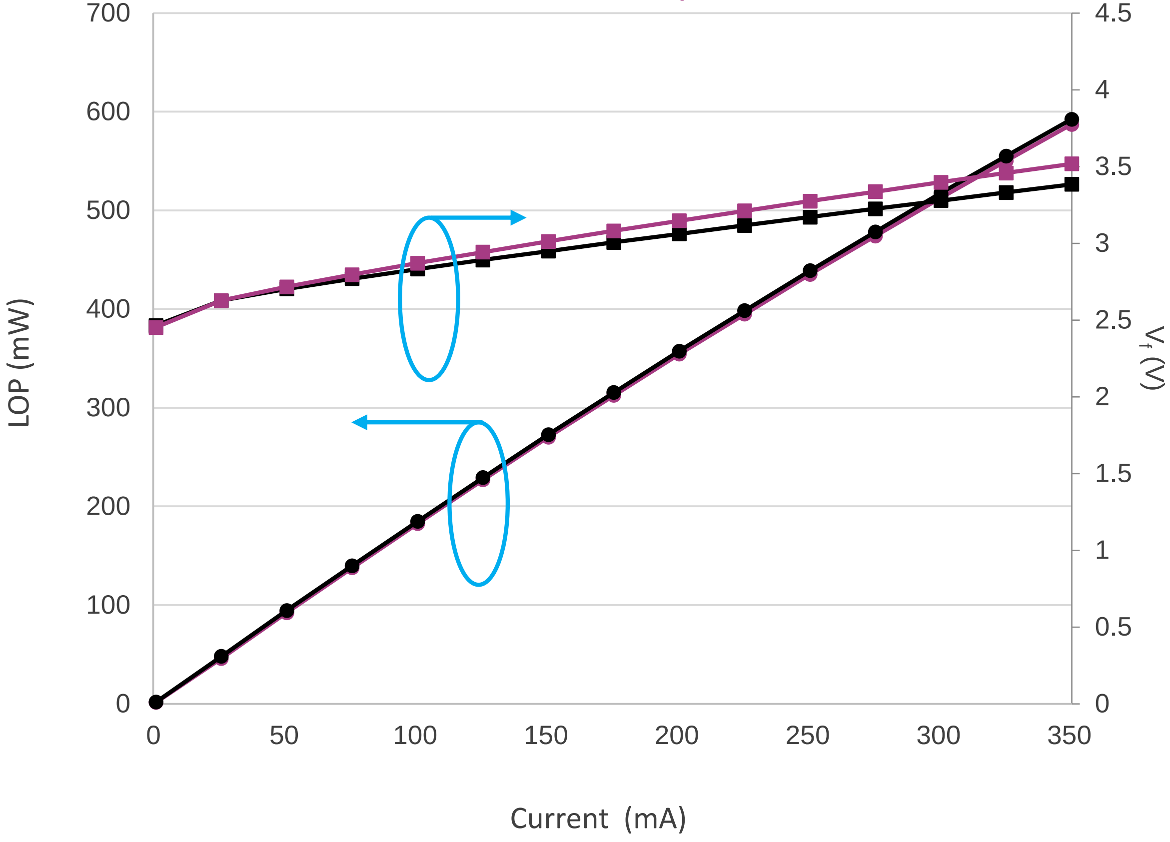


LED WITH RPCVD p-GaN, COMPARED TO COMMERCIAL FULL BLUE LED





LIGHT OUTPUT AND V_f VS CURRENT

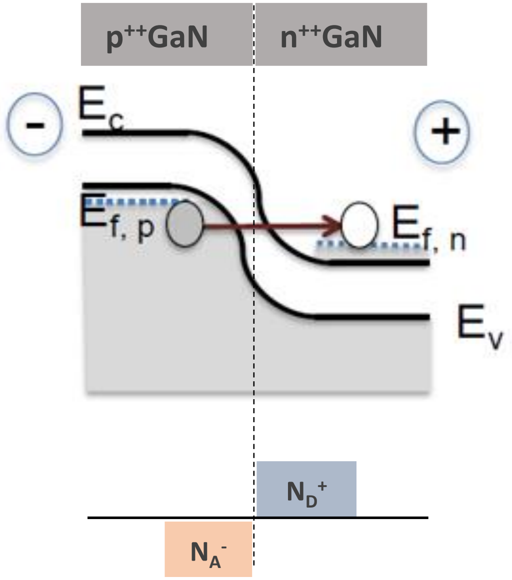


KEY:
Blue LED with RPCVD p-GaN   Commercial full blue LED

LED PROCESSING DETAILS

- Top ITO thickness: 100 nm
- Metallization: Cr/Al/Pt/Au alloy
- Pad size: 100 ± 5 μm
- Chip size: 1140 x 1140 (± 25) μm^2

TUNNEL JUNCTION IN REVERSE BIAS



Electron ←→ hole carrier conversion

$$w \propto \sqrt{\frac{N_A + N_D}{N_A N_D}}$$

Being a high bandgap material, GaN has a wide depletion layer width

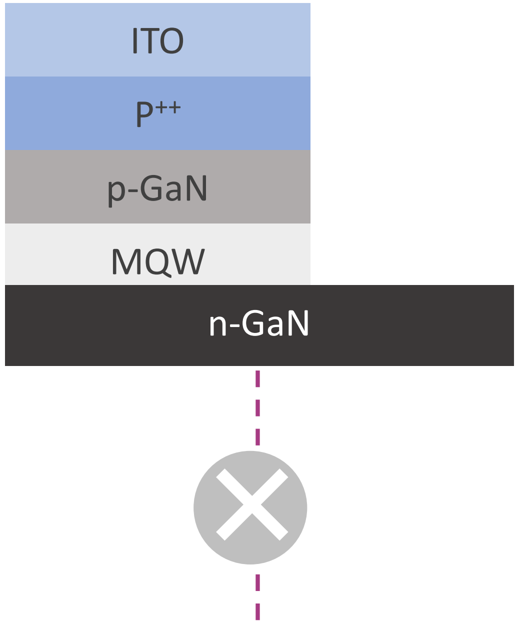
STANDARD n^{++} GaN/p^{++} GaN TUNNEL JUNCTION REQUIREMENTS:

- High doping for both p^{++} GaN and n^{++} GaN
- **Sharp dopant profile at TJ interface (particular for Mg which is difficult to achieve with MOCVD)**
- Buried activated p-GaN

RPCVD has advantages in all aspects

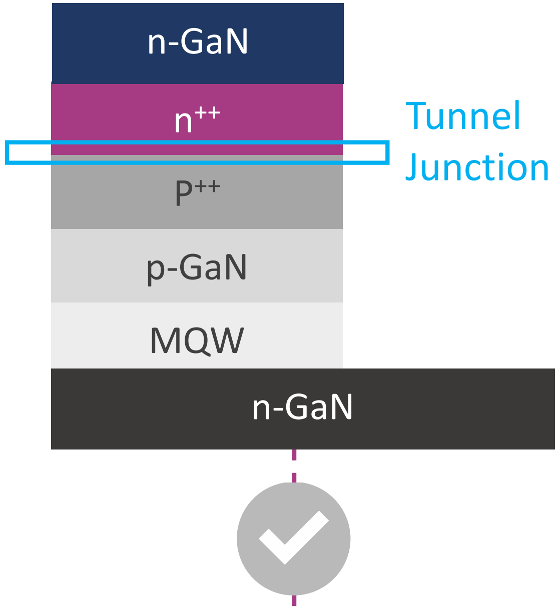
GaN TUNNEL JUNCTION/n-GaN AS TOP CONTACT TO REPLACE ITO

CONVENTIONAL LED



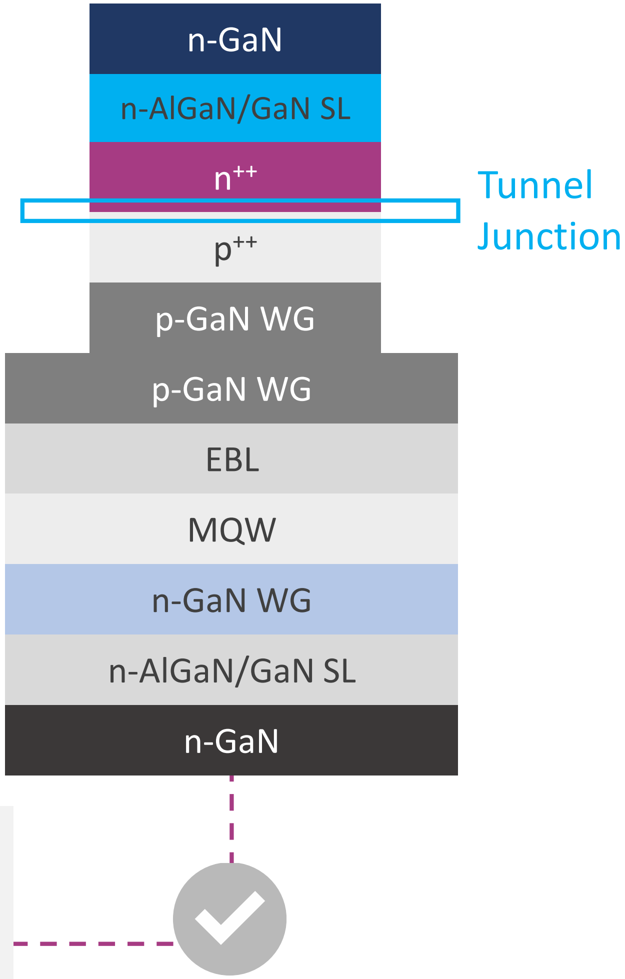
- *ITO required for current spreading*
- *ITO not fully transparent*

LED with TUNNEL JUNCTION



- *Replacement of ITO with Tunnel Junction/n-GaN contact*
- *Simplified processing of n-GaN contacts*

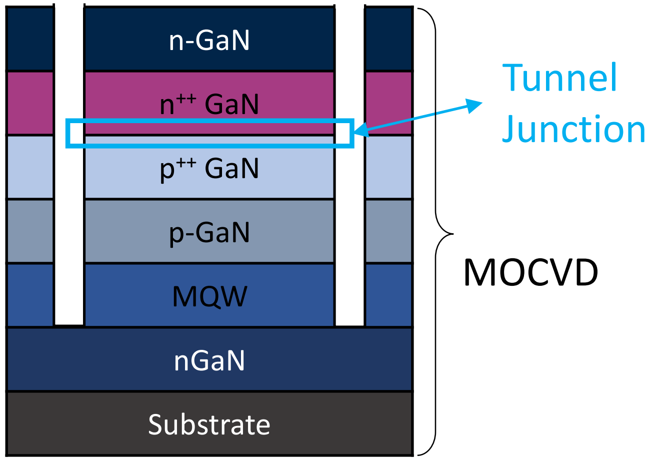
LASER DIODE with TUNNEL JUNCTION



Replacement of highly-resistive p-AlGaN cladding and p-GaN contact layers with low-resistance TJ/n-AlGaN cladding and n-GaN contact layers.

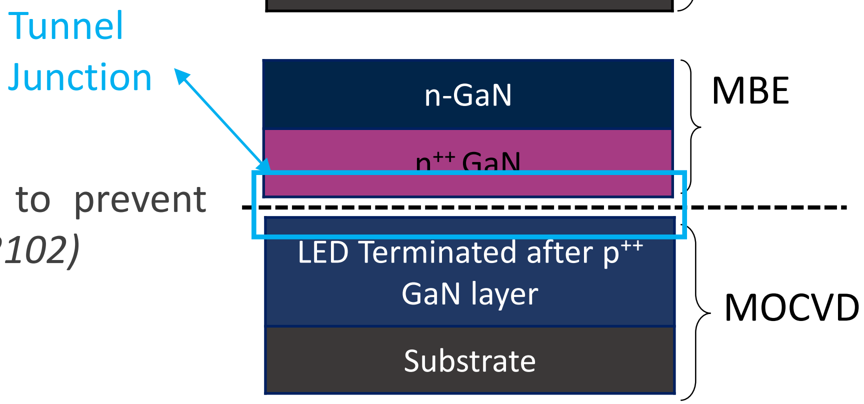
TUNNEL JUNCTION WITH BURIED p-GaN

MOCVD-GROWN TUNNEL JUNCTIONS



- High hydrogen content & Mg-H complex formation in p-GaN
- Post-growth annealing required for p-GaN activation
- Poor Hydrogen Diffusion in vertical direction due to high hydrogen diffusion barrier of n-GaN (*Y. Kuwano et al. Jpn. J. Appl. Phys. 52 (2013) 08JK12*)
- Requires lateral activation involving exposed edges and constrains chip sizes

HYBRID MOCVD/MBE TUNNEL JUNCTIONS

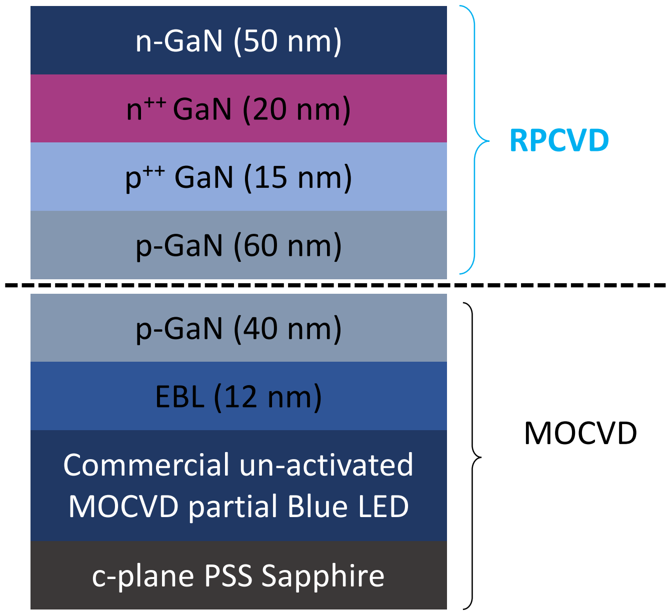


- LED Grown by MOCVD up to and including p-GaN and p^{++} layers
- n^{++} GaN and n-GaN layers grown by MBE in low hydrogen environment to prevent passivation of buried p-GaN (*E C. Young et al. Appl. Phys. Express. 9 (2016) 022102)*
- MBE has scalability limitations

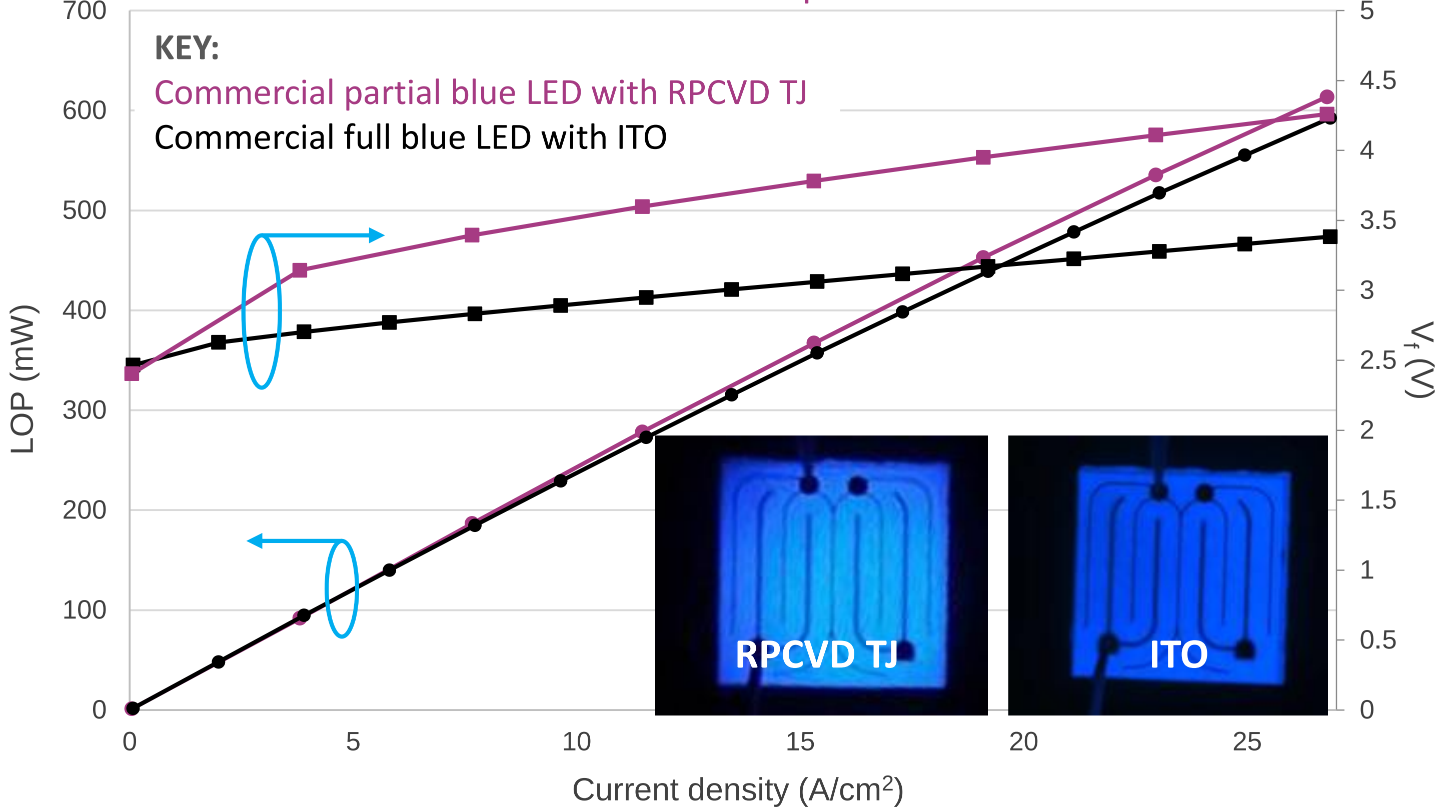
RPCVD TUNNEL JUNCTIONS

- ***Scalable technology (compatible with MOCVD equipment)***
- *RPCVD growth of n-GaN or both p-GaN and n-GaN to achieve **Activated As-Grown** buried p-GaN Junctions*

RPCVD TUNNEL JUNCTION



LIGHT OUTPUT AND V_f VS CURRENT

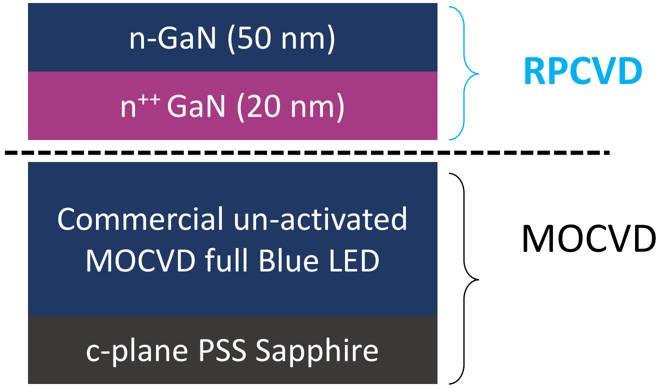


LED PROCESSING DETAILS

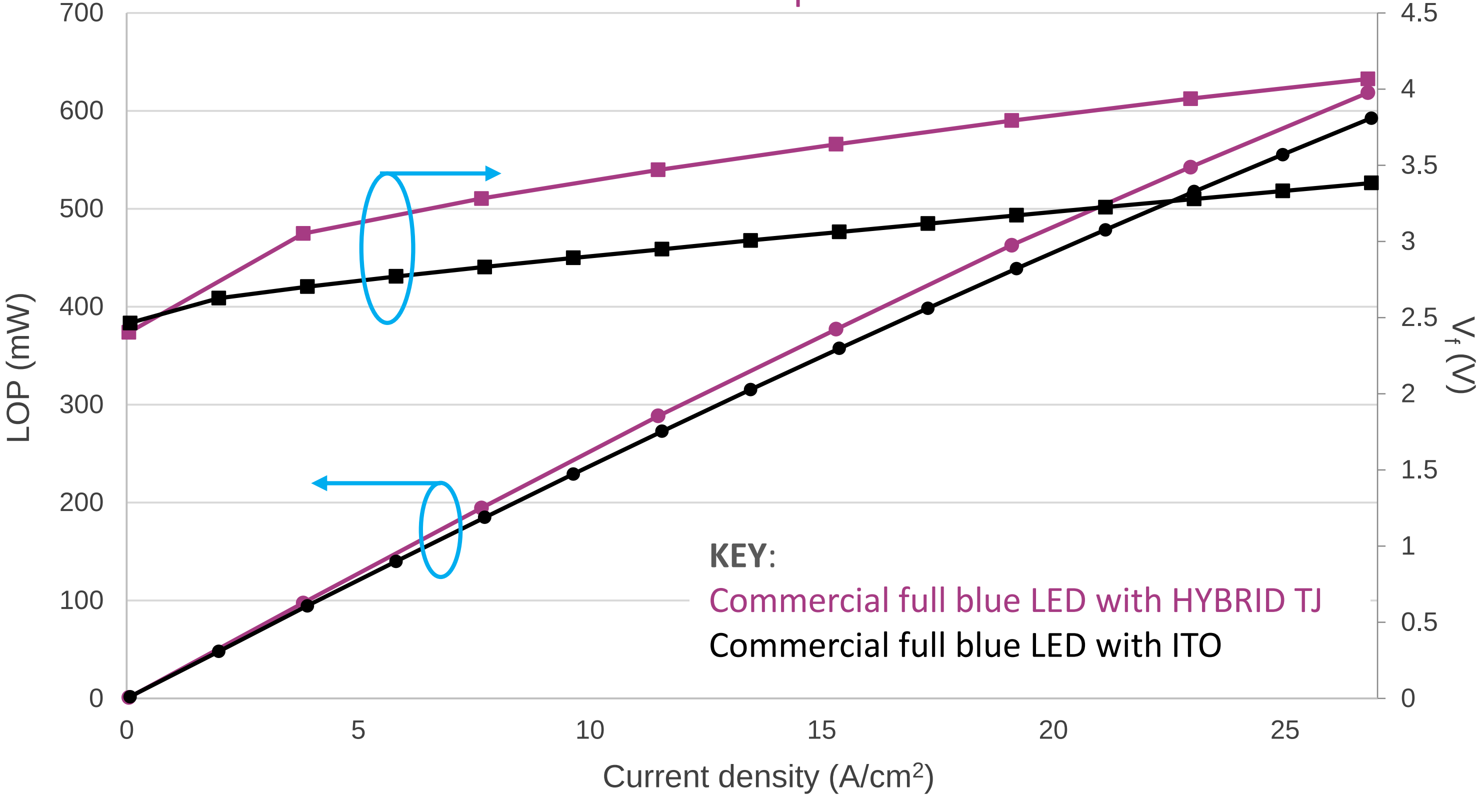
- ITO thickness: 100 nm on full LED & none on LED with Tunnel Junction
- Metallization: Cr/Al/Pt/Au alloy
- Pad size: 100 ± 5 μm
- Chip size: 1140 x 1140 (± 25) μm^2

Structure	EL (packaged) data at 26 A/cm^2				
	Size (mm x mm)	LOP (mW)	ΔLOP (%)	V_f (V)	ΔV_f (V)
LED with RPCVD TJ	**1.14 x 1.14**	**614**	**+3.7**	**4.26**	**+0.88**
LED with ITO	1.14 x 1.14	592	-	3.38	-

RPCVD HYBRID TUNNEL JUNCTION



LIGHT OUTPUT AND V_f VS CURRENT

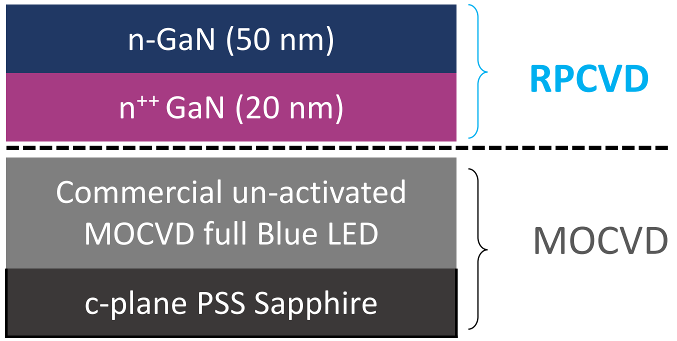


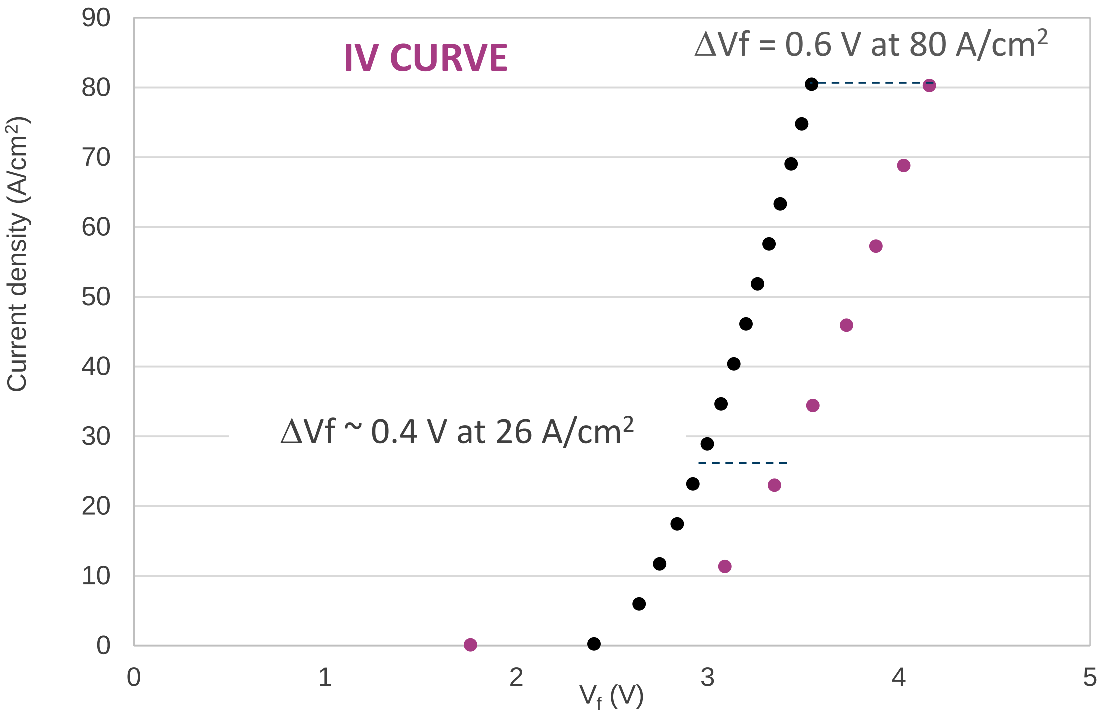
LED PROCESSING DETAILS

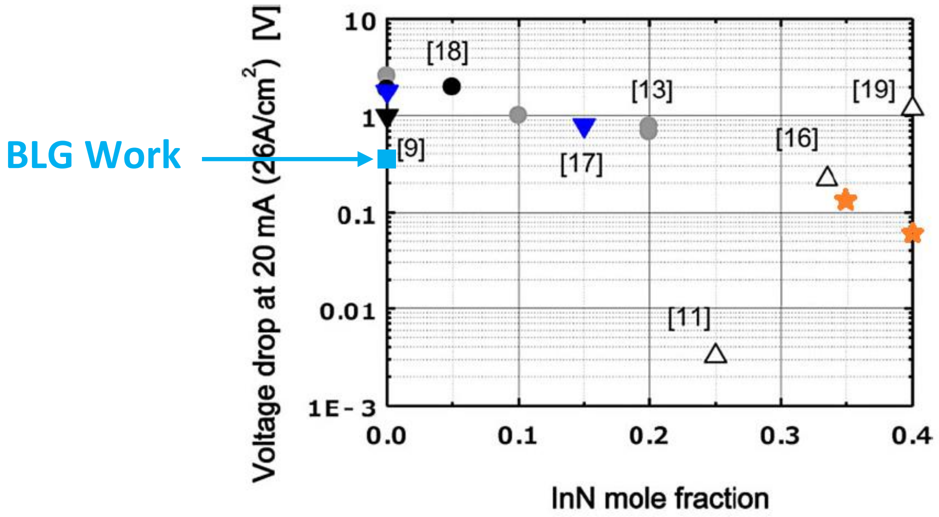
- ITO thickness: 100 nm on full LED & none on LED with Tunnel Junction
- Metallization: Cr/Al/Pt/Au alloy
- Pad size: 100 ± 5 μm
- Chip size: 1140 x 1140 (± 25) μm^2

Structure	EL (packaged) data at 26 A/cm^2				
	Size (mm x mm)	LOP (mW)	ΔLOP (%)	V_f (V)	ΔV_f (V)
LED with hybrid TJ	**1.14 x 1.14**	**618**	**+4.4**	**4.06**	**+0.68**
LED with ITO	1.14 x 1.14	592	-	3.38	-

RPCVD HYBRID TUNNEL JUNCTION – LOW V_f





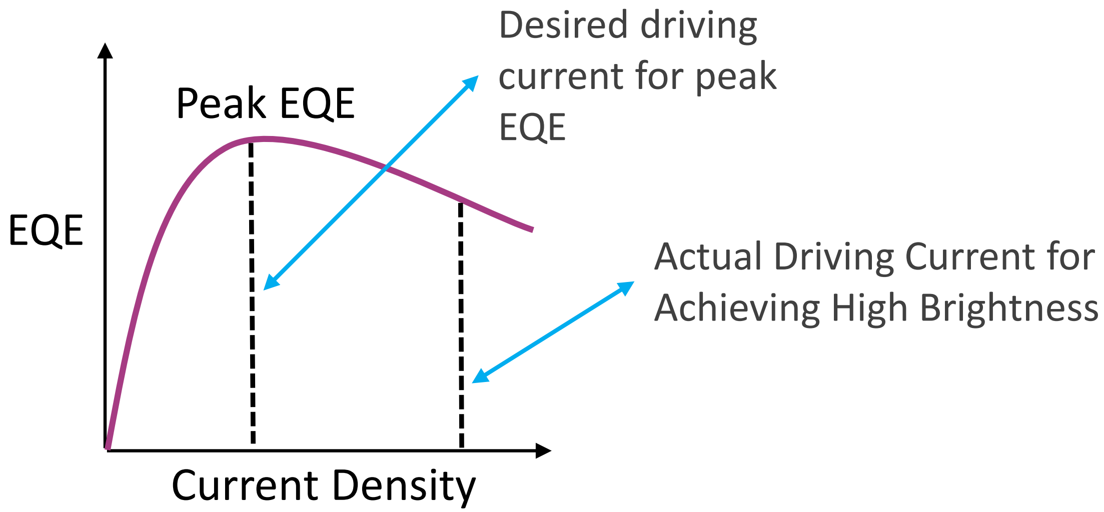


D. Minamikawa et al. Phys. Status Solidi B. 252 NO. 5, 1127-1131 (2015)

Structure	EL (packaged) data		
	Current density (A/cm²)	V_f (V)	DV_f (V)
LED with hybrid TJ (0.66 x 0.66 mm²)	26	3.40	**+0.40**
	80	4.16	**+0.62**

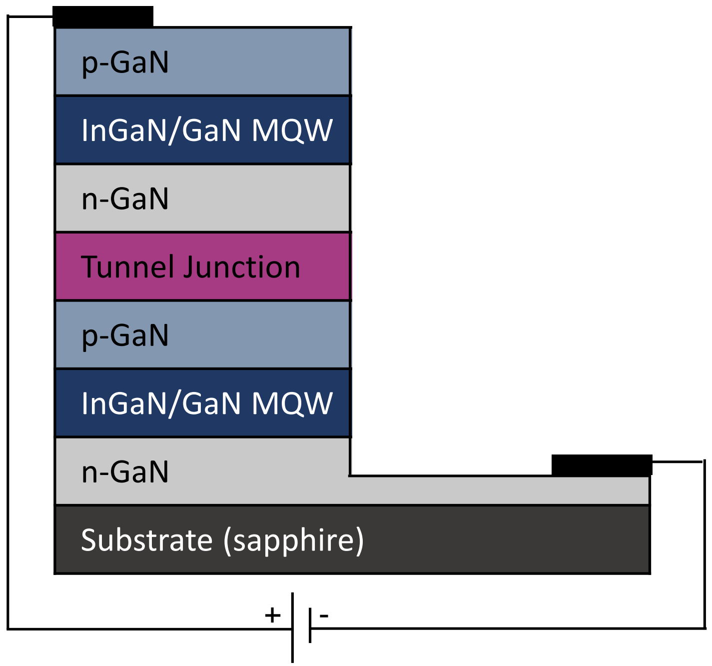
FUTURE WORK: CASCADE LED

EFFICIENCY DROOP IS A MAJOR ISSUE FOR HIGH BRIGHTNESS LED APPLICATIONS



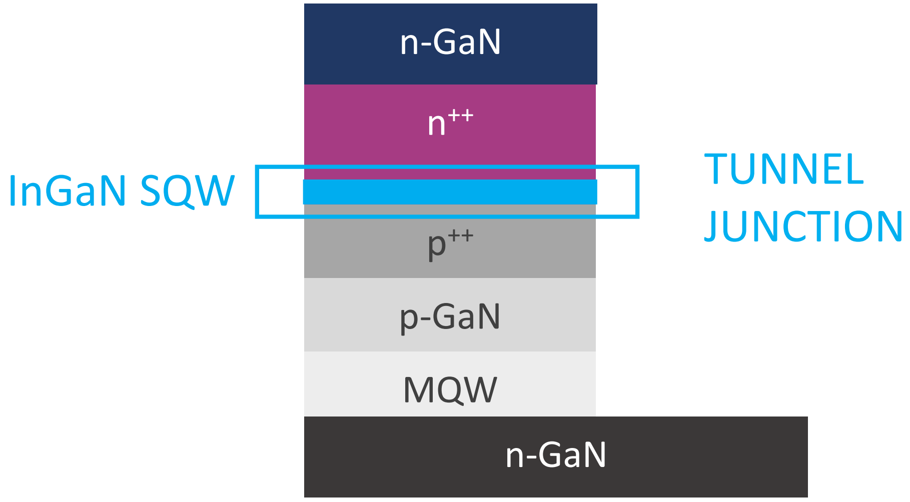
CASCADE LEDS:

- Compact size & lower cost due to more LEDs grown in a single wafer – high brightness in a small area
- Good candidate for automotive lighting application



FUTURE WORK: Polarisation Engineered InGaN tunnel junction

LED WITH InGaN TUNNEL JUNCTION



POLARISATION ENGINEERED InGaN TUNNEL JUNCTION:

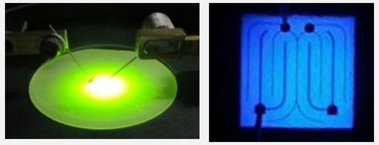
- Reduced depletion layer width due to high density dipole sheet charge developed by InGaN SQW
- High indium content InGaN SQW has been successfully grown by RPCVD
- RPCVD can combine polarisation engineered InGaN SQW with highly doped p^{++} and n^{++} layers to reduce the depletion layer width even further to achieve much lower V_f

FUTURE PLANS – RPCVD ROADMAP TO FULL-SUITE SOLUTION

RPCVD ROADMAP – FROM A COMPLEMENTARY SOLUTION TO A STAND-ALONE PLATFORM

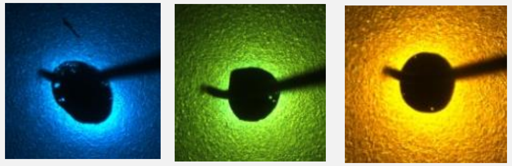
RPCVD VALUE ADDS

RPCVD + MOCVD



Hybrid MOCVD/RPCVD solution to help enhance or enable:

- RPCVD p-GaN for high-performance LEDs
- RPCVD Tunnel Junction for ITO replacement of LEDs



- RPCVD RGB LEDs
- RPCVD Tunnel Junction for cascade LED to overcome efficiency droop

RPCVD + MOCVD

All RPCVD

Standalone RPCVD solution for group III-Nitride based applications

- B, In, Ga, Al Nitrides
- Large Si substrates
- CMOS integration

TIME

BLUGLASS

SUMMARY

BluGlass has demonstrated high quality growth at low temperature in a low hydrogen environment on a scalable RPCVD platform compatible with MOCVD on planar sapphire

Success in demonstrating that RPCVD can enable:

- LEDs using tunnel junctions
- long wavelength InGaN based RGB microLEDs

BluGlass is actively seeking new partners and projects to advance nitride application opportunities using RPCVD

Thank you

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