



MAKING A **MATERIAL** DIFFERENCE

MicroLED Connect

MOCVD for MicroLEDs

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Veeco Instruments, inc.



Acknowledgements

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- Eric Armour
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Outline

MicroLED applications

- Displays
- Interconnects
- Manufacturing

What is MOCVD

- Introduction to epitaxy
- MOCVD process
- MOCVD system and components

MOCVD for microLED manufacturing

- GaN
- GaAs



MAKING A **MATERIAL** DIFFERENCE

MicroLED Applications

Display

MicroLED display commercialization is beginning

- Next-generation high-performance display applications
- Initial products in Smart Glasses and some wearables
- Luxury large format TVs
- Small volumes and high prices for today's early products



JBD



Rokid



Samsung



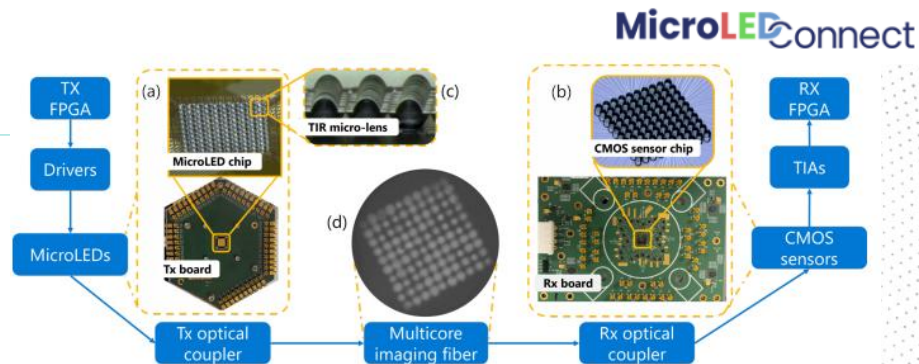
Garmin



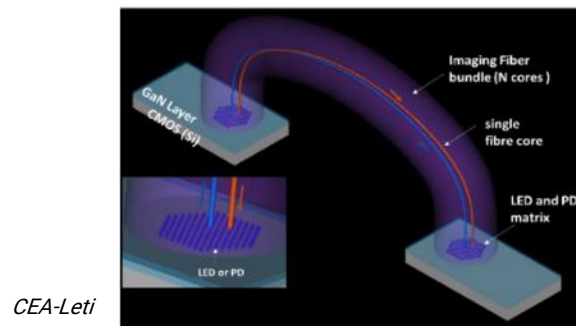
Optical Interconnects

Optics are moving closer to the chip

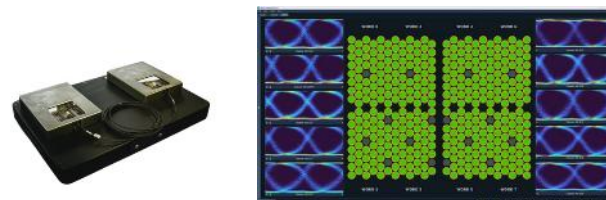
- Optics are now part of the computing fabric
- Bandwidth and energy limitations are moving interconnects from copper to optical
- Potential improvements in key metrics with microLEDs
 - Bandwidth
 - Bandwidth density
 - Energy/bit for data transfer
- MicroLEDs are positioned to address interconnects within server racks: **Scale-Up**



Mosaic:
Microsoft



CEA-Leti



Avicena: microLED Optical Interconnect
Evaluation Kit



MicroLED Manufacturing Challenges: Epiwafers

Epiwafers impact manufacturing in several areas

Technology

Red LED performance needed, particularly for InGaN-based materials

Small die size challenges

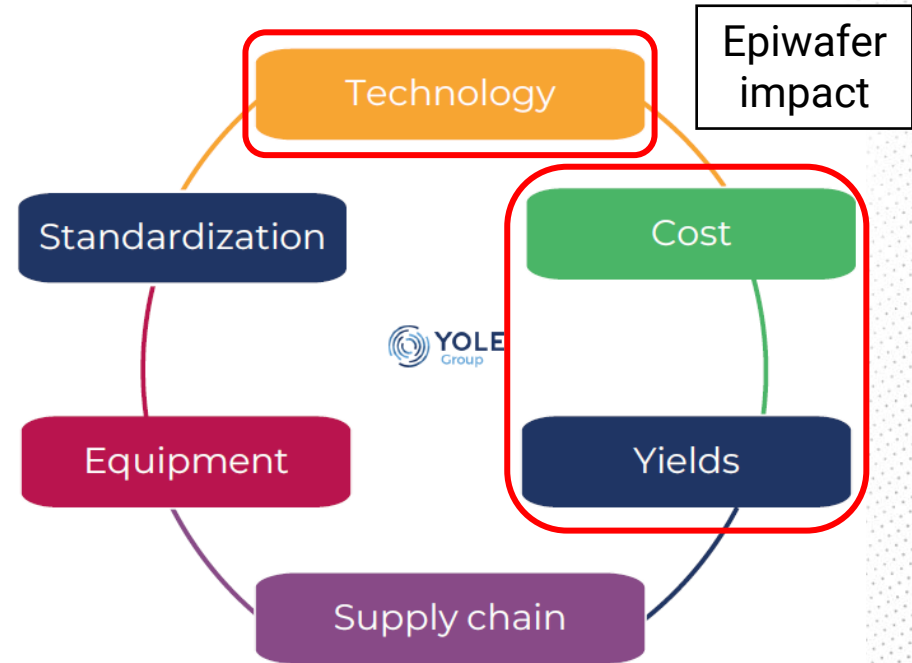
Continue move to larger substrate size

Cost

Reduce per wafer cost, increase productivity, larger substrates

Yield

Maximize epiwafer yield to improve number of good die and reduce downstream processing steps (binning, repair, etc.)



MicroLED Epiwafer Manufacturing

Process Challenges

Metric

Impact

Within wafer wavelength uniformity

Within wafer thickness uniformity

Defectivity

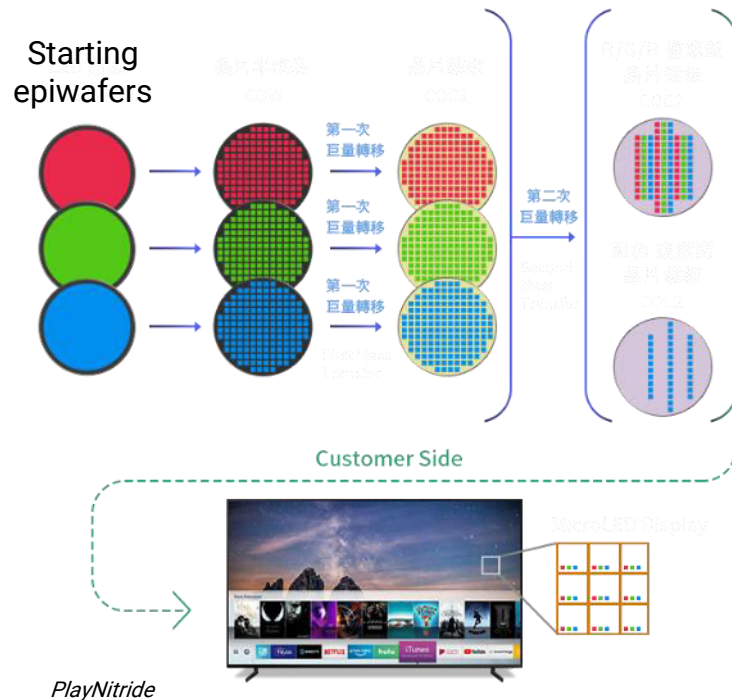
Wafer-to-wafer repeatability

Run-to-run repeatability

Tool-to-tool repeatability

Device yield, total cost
Display: color variation, transfer field uniformity
Interconnect: less stringent specs for uniformity

Overall fab-level yield and operational costs
Complexity of managing epi tool fleet



The MOCVD process must deliver high-volume manufacturing performance to enable microLED-based products



MOCVD Basics

Epitaxial Crystal Growth

■ Epitaxy

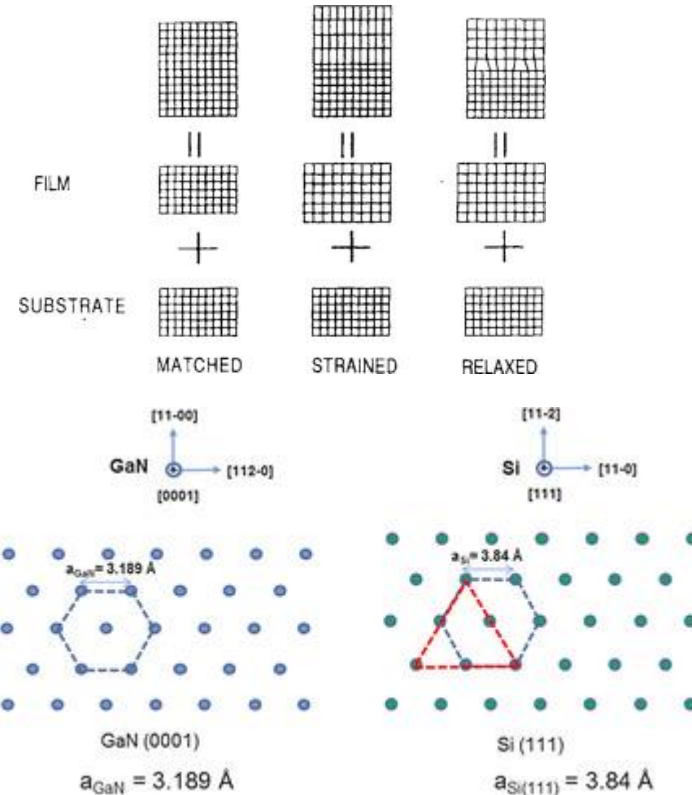
- Growth of thin single crystals of one material on a crystal plane of the same (homoepitaxy) or another (heteroepitaxy) material, such that the two materials have a defined, relative structural orientation
- Thin solid film or layer on a crystal surface → **Epilayers**

■ Main rules of epitaxy

- Matching of crystal symmetry between the substrate and the epilayer
- Misfit between lattice constants of substrate and epilayer should be minimal
- Control defect formation during the growth of the layers

■ Examples of Epitaxy

- GaAs on GaAs (Homoepitaxy) (misfit value = 0)
- AlGaAs on GaAs (Heteroepitaxy) (misfit value > 0)
- GaN on Si (Heteroepitaxy) (misfit value >> 0)



III-V and III-N Materials for MicroLEDs

MicroLED materials

GaAs

- GaAs
- AlGaAs
- AlInGaP
- AlInP
- GaP

GaN

- GaN
- InGaN
- AlGaN

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
hydrogen 1 H 1.0079																	helium 2 He 4.0026
II												III	IV	V	VI		
lithium 3 Li 6.941	beryllium 4 Be 9.0112											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
potassium 19 K 39.098	calcium 20 Ca 40.078											aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
rubidium 37 Rb 85.468	strontium 38 Sr 87.62											gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
cesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 * lanthanum 57 La 138.91	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	polonium 84 Po (209)	astatine 85 At (210)	radon 86 Rn (222)
francium 87 Fr (223)	radium 88 Ra (226)	89-102 ** actinoids	lawrencium 103 Lr (262)	rutherfordium 104 Rf (261)	dubnium 105 Db (262)	seaborgium 106 Sg (266)	bohrium 107 Bh (264)	hassium 108 Hs (269)	meitnerium 109 Mt (268)	ununnium 110 Uun (271)	ununium 111 Uuu (272)	unubium 112 Uub (277)	ununquadium 114 Uuq (289)				

*lanthanoids

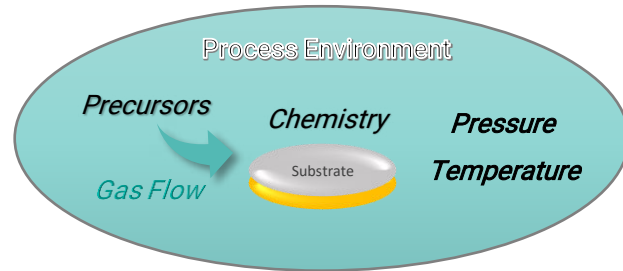
**actinoids

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm (145)	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac (227)	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np (237)	plutonium 94 Pu (244)	americium 95 Am 243	curium 96 Cm (247)	berkelium 97 Bk (247)	californium 98 Cf (251)	einsteinium 99 Es (252)	fermium 100 Fm (257)	mendelevium 101 Md (258)	nobelium 102 No (259)

MOCVD – What is it?

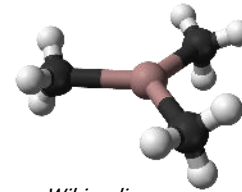
Metalorganic Chemical Vapor Deposition

- MOCVD is a growth technique for the creation of epilayers of semiconductor materials
- Gas sources are introduced into a controlled environment to create layers of materials with precisely controlled properties

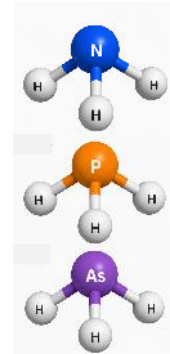


- Sequential epitaxial layers are formed in a stack to create the basic structure of a semiconductor device

TMAI
TMGa
TMIn

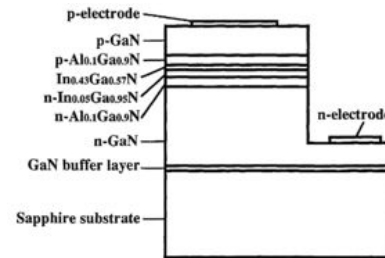


Wikipedia



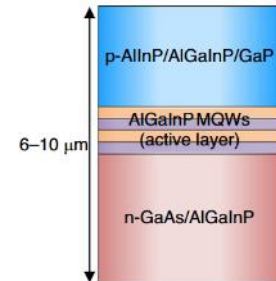
NH_3
 PH_3
 AsH_3

GaN-based LED



Nakamura et al., 1995

AlInGaP-based LED



T.S. Kim et al., 2025

MOCVD System Block Diagram

Gas Handling System

- Precisely deliver gases to system
- Rapid gas switching for abrupt interface control
- Leak tight to prevent oxygen contamination

Process Module

- Place where material deposition occurs
- Deliver gases to wafer surface

System Controls Software

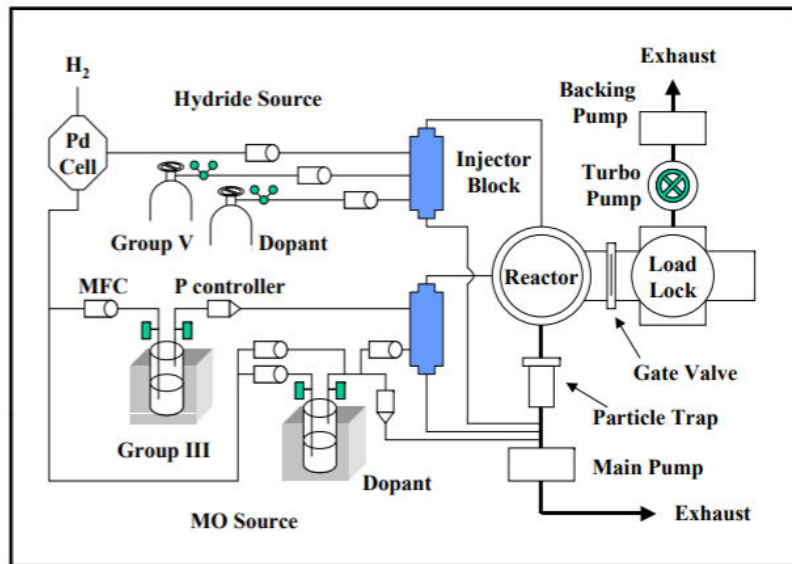
- Provide monitor and indication of system
- Data recording
- Process control software to define growth parameters

Exhaust System

- Control growth chamber pressure
- Remove byproducts from exhaust gas stream

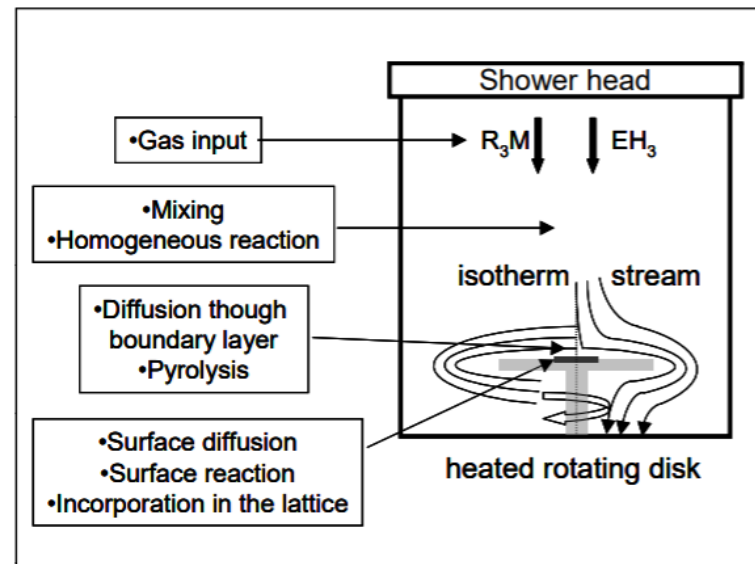
MOCVD System Schematic

System Overview

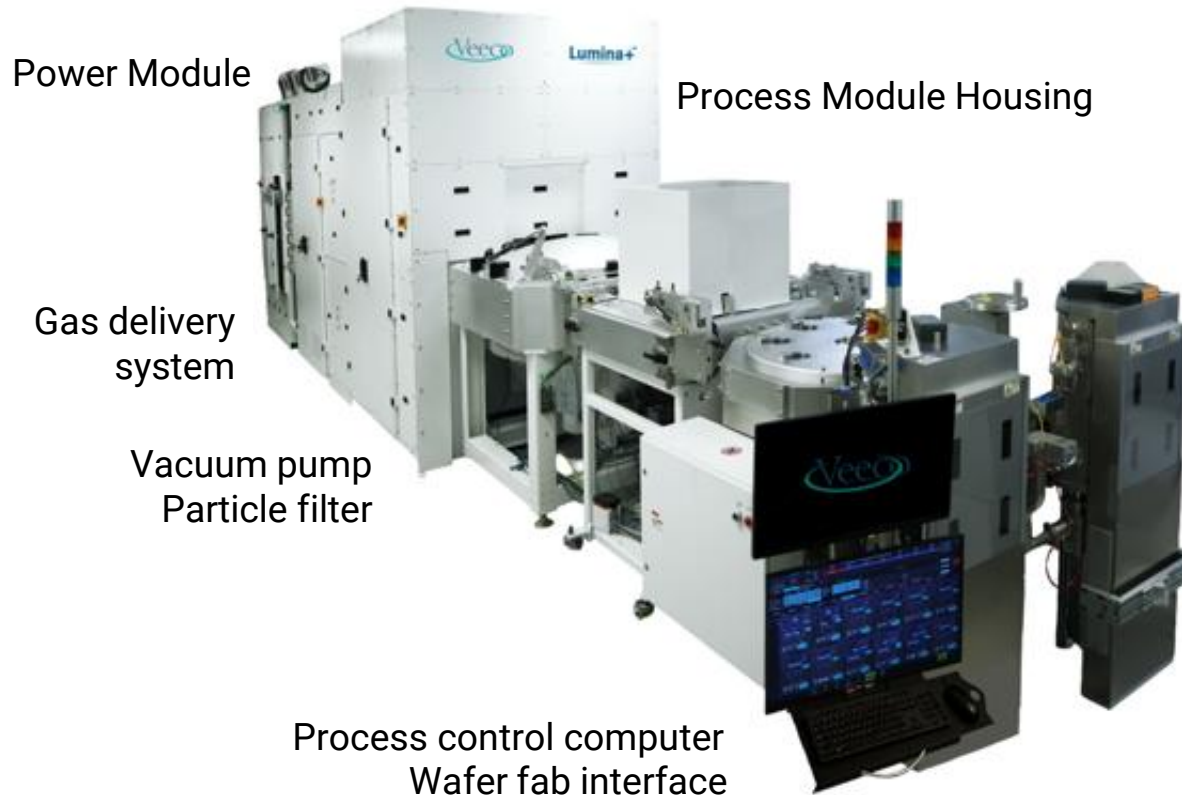


W. Lee, RPI

MOCVD Process Module "Reactor" Schematic



MOCVD System Image



300mm Si wafer handling



Automated wafer handling

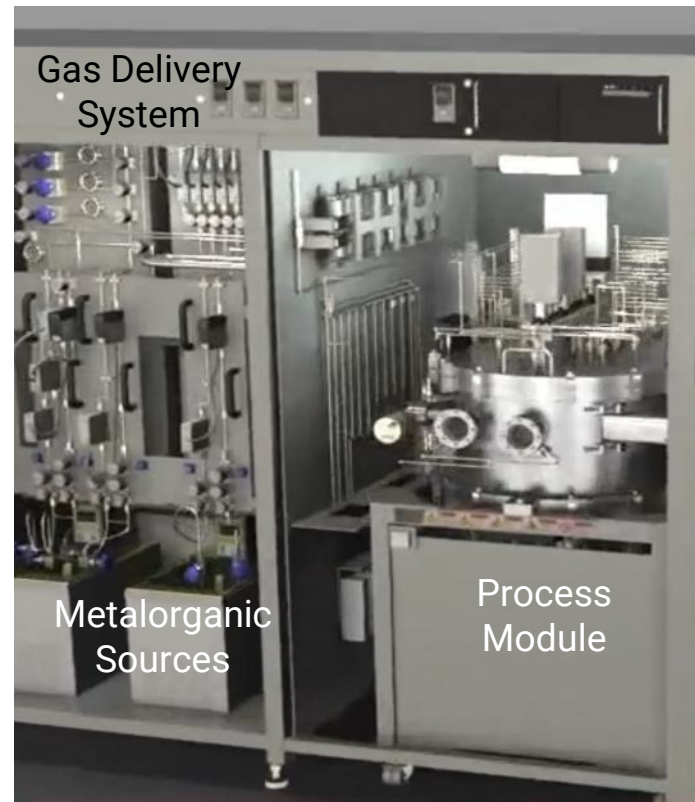
MicroLED Substrates:

GaAs: 150mm & 200mm
Sapphire: 150mm & 200mm
Si: up to 300mm

MOCVD Process Module

- Modern MOCVD system configuration (AsP)
 - 6+ MO sources
 - Hydrogen, nitrogen, hydride, and gas dopant sources
 - > 30 MFCs
 - Fully automated wafer handling for low defectivity
- Wide process window for LED device stack
 - GaN
 - 650 – 1100 °C
 - Variable pressure: 50 – 200+ Torr
 - 100% H₂ to 100% N₂ process environment
 - 0.1 – 5+ $\mu\text{m/hr}$ growth rate

The MOCVD system must be capable of handling a wide range of process conditions





MOCVD Process Elements

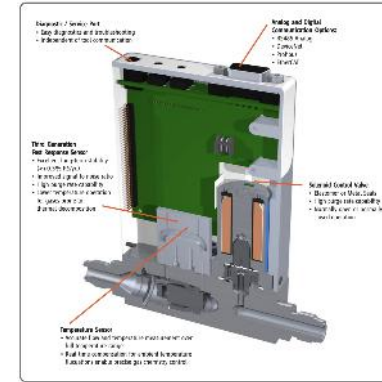
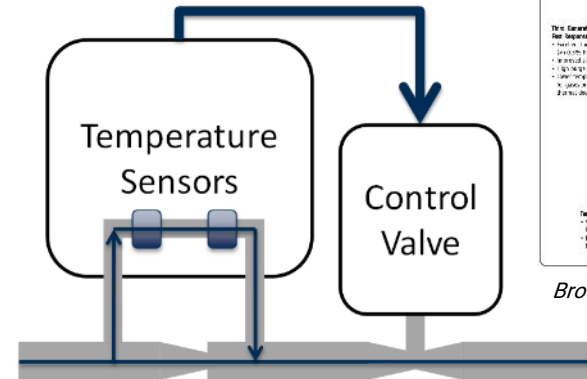
Gas Flow Control

■ Mass Flow Controller (MFC)

- A portion of the gas flow passes through a tube incorporating two temperature sensors
- A temperature difference results that is proportional to the mass flow through the controller

■ Modern MFCs offer multiple advanced gas control features

- Digital communications for rapid communication of multiple parameters
- Device monitoring
- Rescaling for wide flow control ranges
- Large dynamic ranges for precise gas delivery
- 10 sccm – 100+ slm flow rates



Brooks Instruments



Brooks Instruments



Horiba



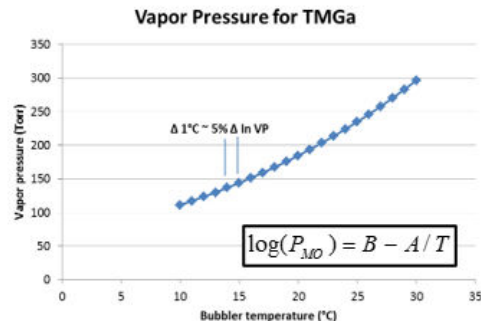
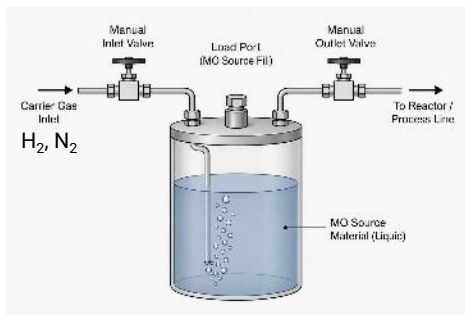
Metalorganic Sources

- Metalorganic (MO) sources are held in special containers called bubblers
- Transport of the MO source occurs via carrier gas that is bubbled through the source material
- For liquid sources, the carrier gas is assumed to be completely saturated by the reagent vapor

MO	Melting point (°C)	State at Room Temperature	Bubbler Temp (°C)	Vapor Pressure (Torr)
TMGa	-15.8	Liquid	15	148.72
TEGa	-82.5	Liquid	25	5.06
TMAI	15	Liquid	25	14.32
TMIn	88	Solid	35	3.82
Cp2Mg	175	Solid	35	0.10



Dock Chemical



$$pV = nRT$$

$$\Omega_{MO} = \frac{\Omega_v \times P_{MO} \times P_0 / P_B}{RT}$$

Ω_{MO} : MO Source Molar Flux, $\mu\text{mol/min}$;
 Ω_v : Carrier gas flow rate, sccm;
 P_{MO} : MO vapor pressure at Temp T, torr;
 P_0 : STD pressure, 101325 Pa;
 P_B : Bubbler regulated pressure, torr;
 R : Ideal gas constant, 8.314 J/mol·K;
 T : MO bubbler Temperature, K.

Typical MOCVD Sources

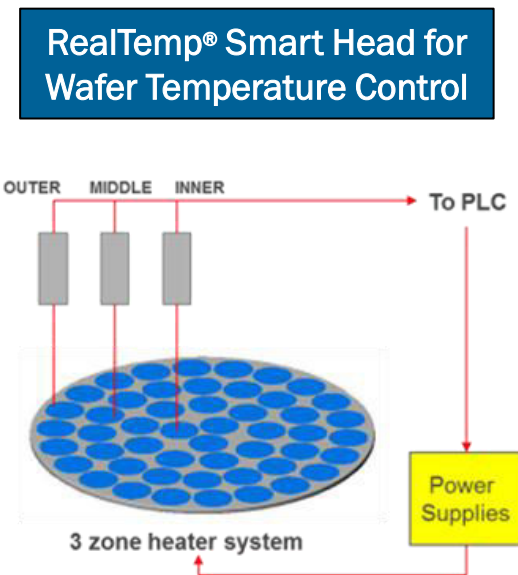
Group III: Trimethyl gallium, Trimethyl aluminum, Trimethyl indium

Group V: Arsine, Phosphine, Ammonia, Tertiarybutyl arsine (TBAs), Tertiary-butyl phosphine (TBP)

Dopants: Carbontetrabromide, Silane, Disilane, Dimethyl zinc, Ethene

Wafer Temperature Control

- In-situ monitoring of the wafer temperature
 - Pyrometer measurement of the growth surface temperature. Wavelength selection based on material and temperature range.
 - Emissivity compensation via reflectance measurement
 - Precise wafer temperature control: $< 1^{\circ}\text{C}$ temperature variation
 - Multi-zone configuration for optimal temperature profile
 - Closed-loop feedback for real time temperature control
 - Applicable to multi-wafer batch tools or single-wafer 300mm tools

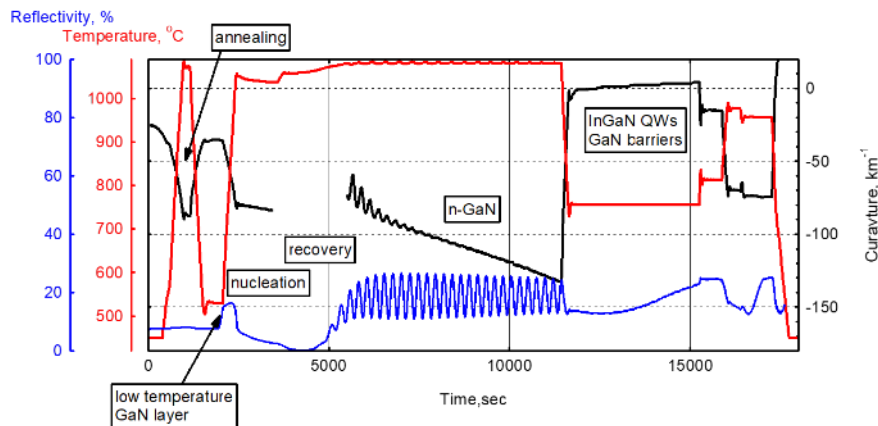


Emissivity-Compensated
Pyrometry (ECP) Wafer
Temperature Control

In-Situ Monitoring

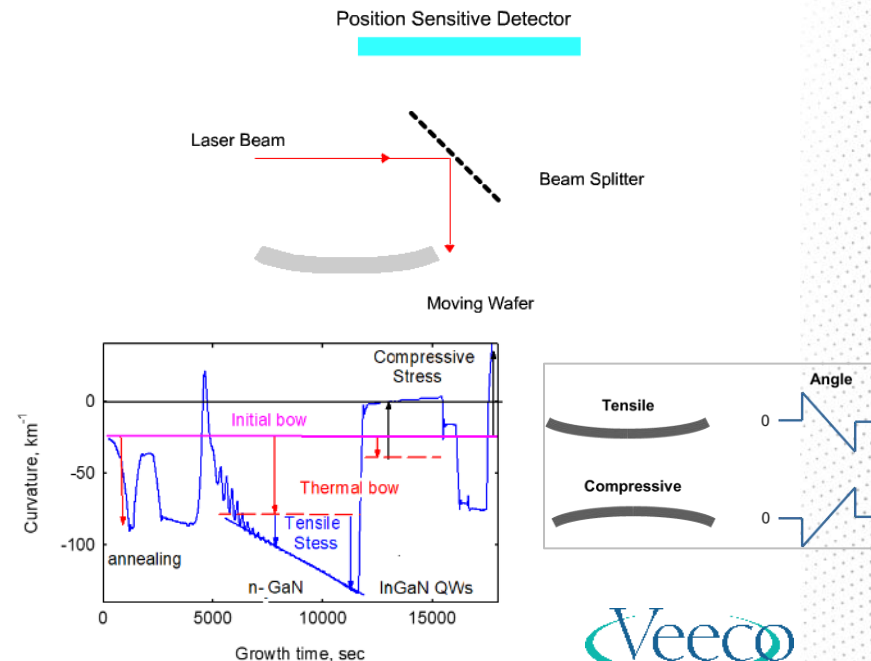
Reflectometry

- Real time measurement of the growth rate and surface morphology of the growing film via



Deflectometry

- Real time measurement and control of epitaxial strain and wafer curvature via





MOCVD Growth

MOCVD Growth Dynamics

- The Navier-Stokes equation describes the fluid flow behavior and properties of the MOCVD process environment
- Users target laminar flow conditions for a stable, repeatable process
- Growth rate
 - Proportional to alkyls partial pressure
 - Inversely proportional to the boundary layer thickness
- Control of the thickness of the boundary layer is critical for uniform growth
 - Film thickness
 - Compositional uniformity
 - Doping uniformity

The Navier-Stokes Equation

$$\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right] = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g}$$

Mass x Acceleration: $\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right]$
 Forces: $-\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g}$

Change in fluid velocity over time: $\frac{\partial \vec{u}}{\partial t}$
 Fluid convection in space: $(\vec{u} \cdot \nabla) \vec{u}$
 Pressure gradient: $-\nabla p$
 Viscous force: $\mu \nabla^2 \vec{u}$
 Body force: $\rho \vec{g}$

Newton's Second Law of Motion

☐ Incompressible flow
☐ Newtonian fluid
☐ Stokesian fluid

R. Walia

$$\text{Growth Rate} \sim D \cdot \frac{C_G}{\delta}$$

C_G – MO concentration at bulk of gas

D – diffusion coefficient

δ boundary layer thickness

Boundary Layer: the thin layer of gas above a surface where the velocity is less than that of the bulk flow velocity due to surface friction effects

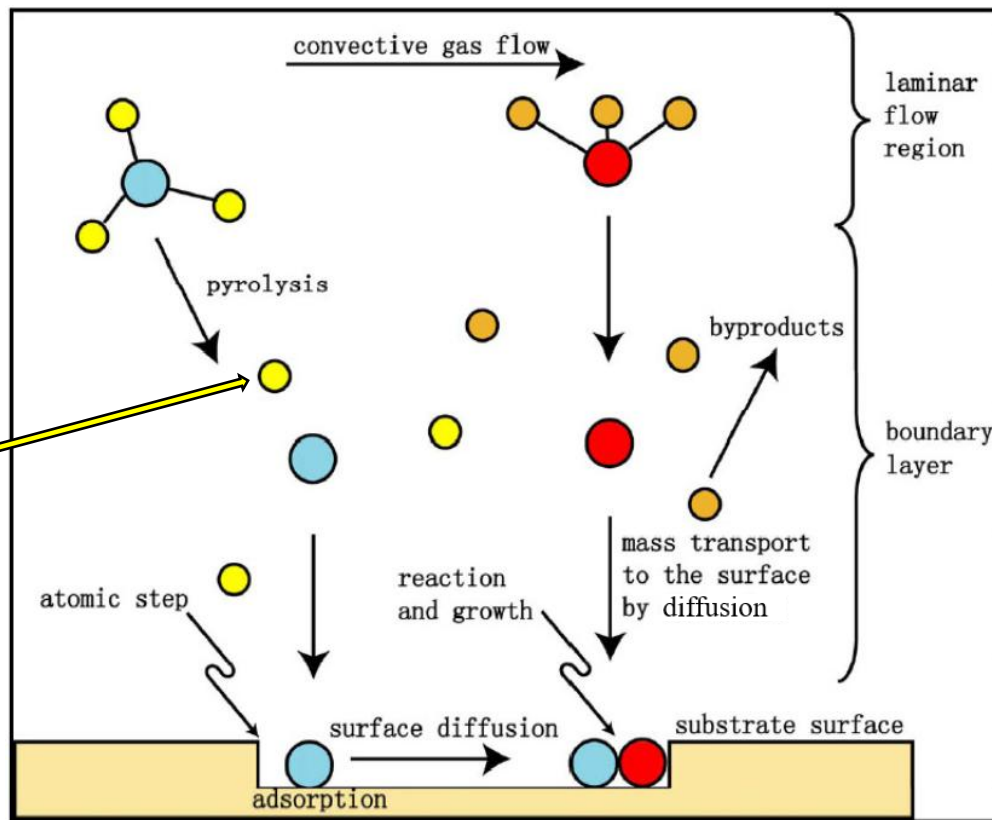
View of the Growth Process

Pyrolysis

Chemical decomposition of metalorganic compound by heat

Ligand

Molecule or atom that is bonded to the central metal atom of the metalorganic molecule (e.g. the CH_3 molecules in the case of TMGa)

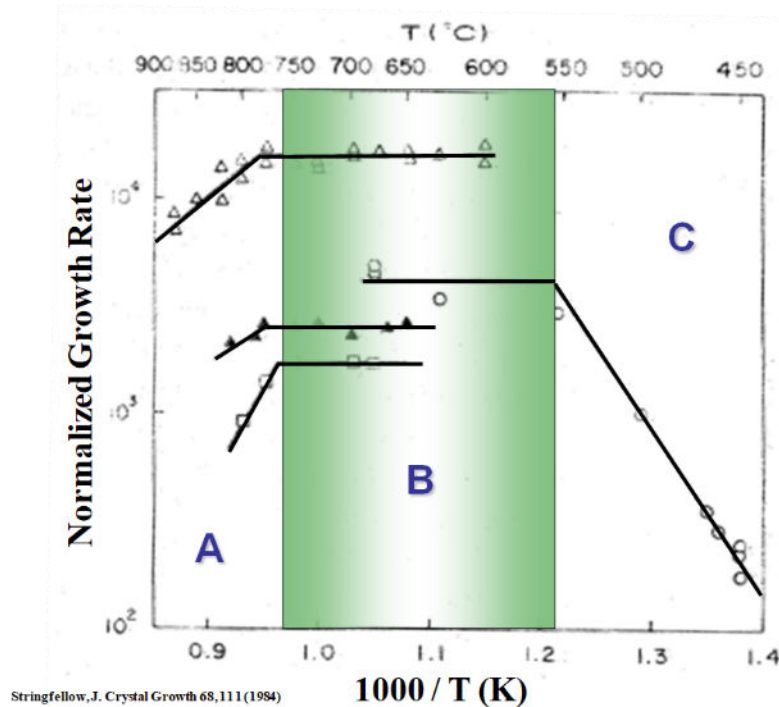


Diffusion

Transport of species to the growth surface through the boundary layer

Surface diffusion to incorporation sites

MOCVD Growth Regimes

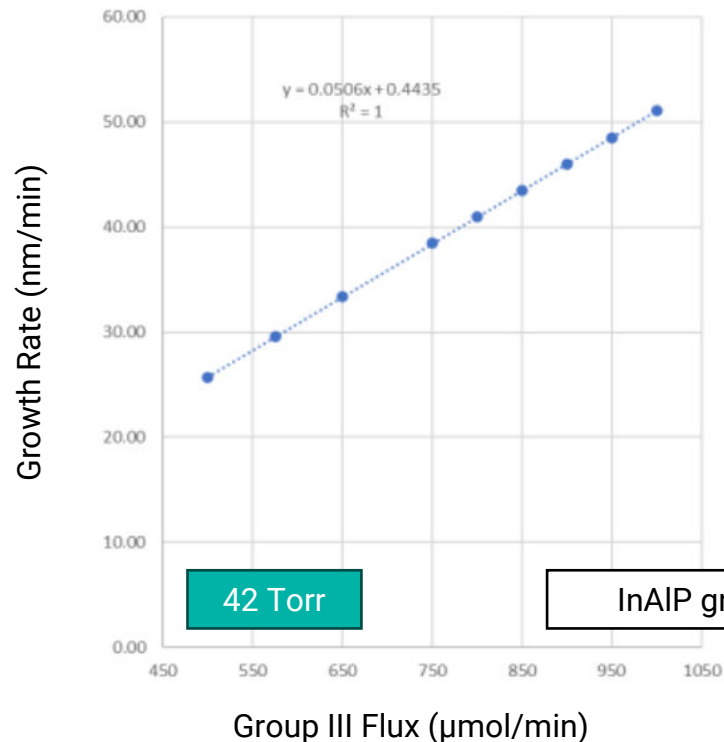


- A. Desorption / Gas Phase Limited Growth
- B. Mass Transport Limited Growth (Diffusion through boundary layer).
- C. Surface Kinetic Limited Growth

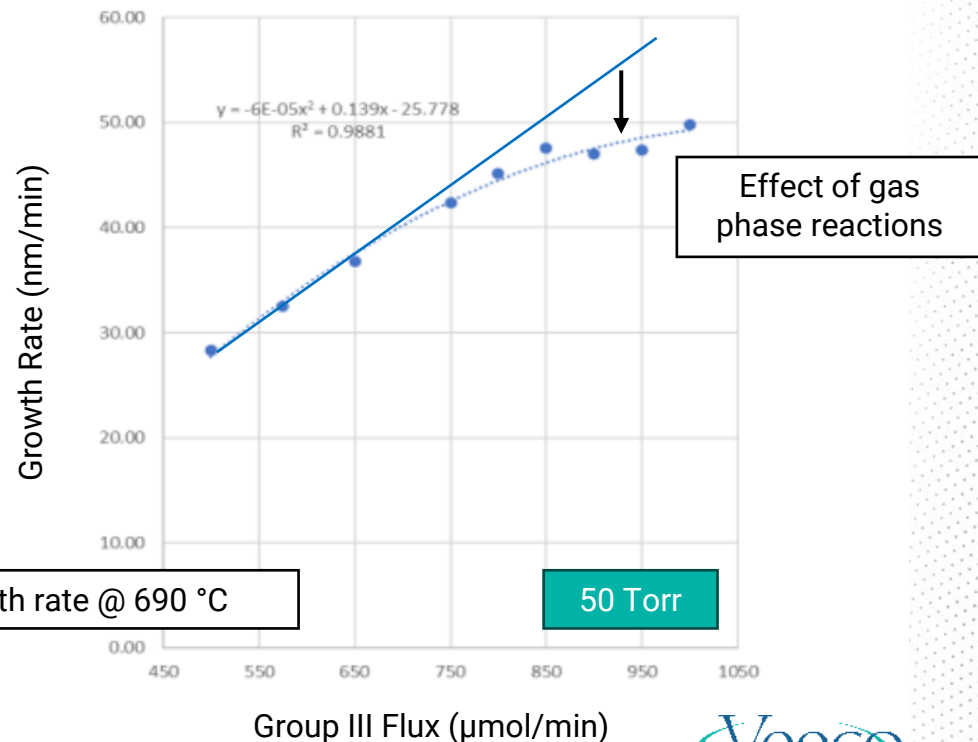
The growth rate is approximately temperature independent in the mass transport limited regime

MOCVD Growth Rate Control: Mass Transport Limited Regime

The growth rate is directly proportional to the metalorganic flux



Gas phase pre-reactions under different process conditions can lead to sub-linear growth rate



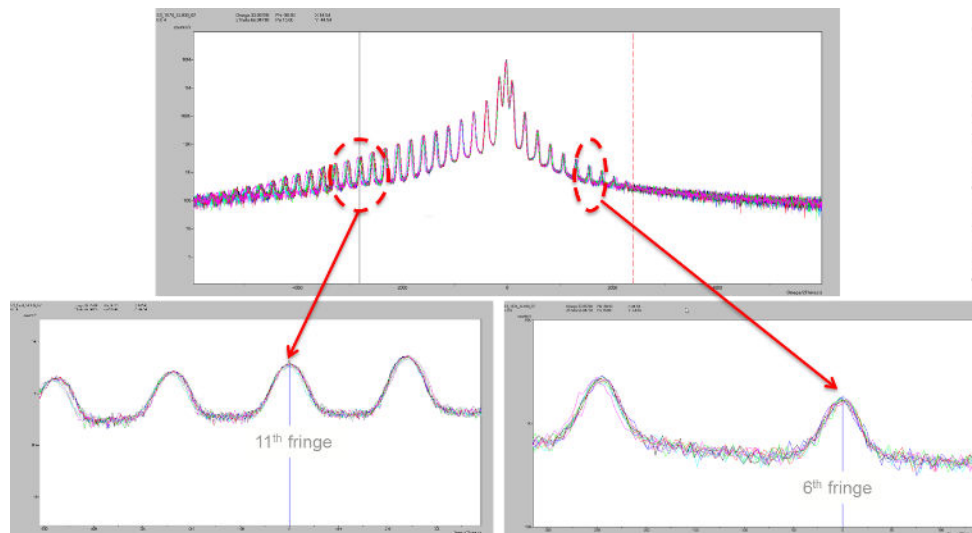
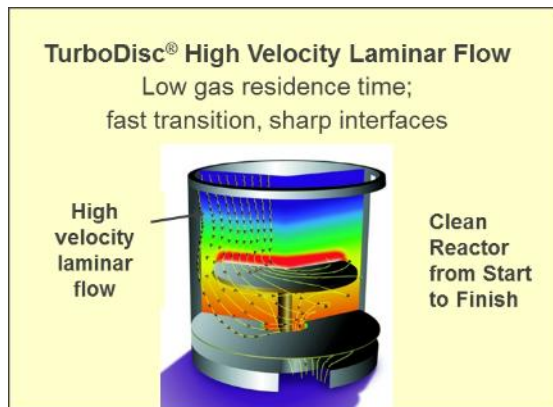
Abrupt Epitaxial Interfaces Drive High Device Performance

- Abrupt interfaces enable optimal device performance
 - Well-defined optical behavior of active regions
 - Good optical and carrier confinement
 - Control of stress and strain of layers
- Optimize process conditions for abrupt composition changes
 - Laminar flow
 - High gas velocities
 - Low residence time in the boundary layer
 - Rapid switching in gas delivery

Demonstrate quality of
interfaces:
short-period super-lattice

GaAs capping layer, 240 seconds, GR ~ 6.2 Å/sec
3.8 nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$, 8.5 second layer, GR ~ 4.5 Å/sec
74 nm GaAs QB, 120 second layer, GR ~ 6.2 Å/s
GaAs buffer
150 mm GaAs Substrate

10x repeat for SPSL



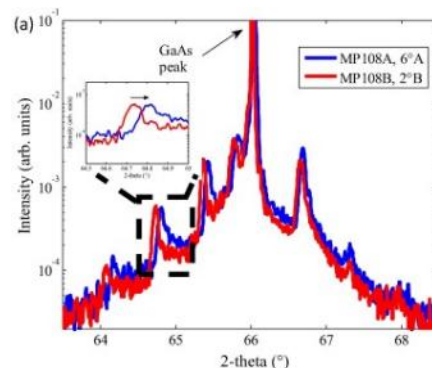
XRD pendellösung satellite fringes show sharp
interfaces and excellent radial uniformity



Tools for Characterizing MOCVD Epilayers

- Crystal quality
 - X-ray diffraction
- Thickness
 - Interferometer
- Optical properties
 - Photoluminescence
 - Electroluminescence
 - Spectroscopy
- Electrical properties
 - Hall Effect
 - CV measurements
 - Leighton measurements
 - IV measurements
- Surface quality
 - Atomic force microscopy
- Others
 - Particles, defectivity
 - SEM, TEM
 - SIMS

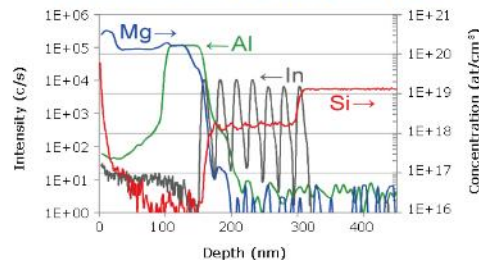
X-ray diffraction scan



I. Sayed et al.

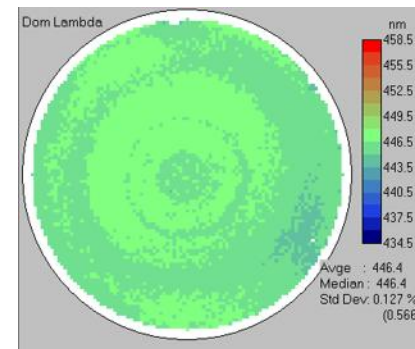
SIMS depth profile

*P- and N-type dopant profiles in AlGaIn/InGaN LED structure
Detection limit better than 1E16 for both Mg & Si*

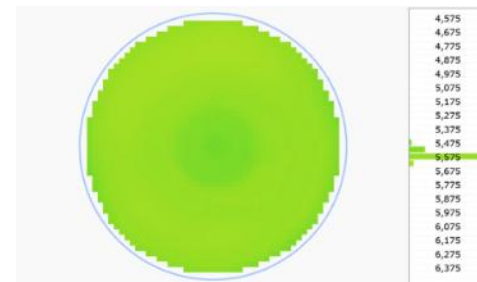


Cameca

Photoluminescence map



Interferometer thickness map



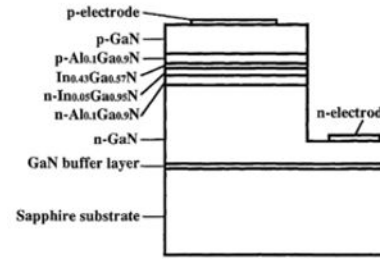


MOCVD of MicroLEDs

MicroLED Device Structure

- Multi-layer epitaxial stack
 - Properties control wavelength and intensity of emission
- N- and p-type layers for electrical device operation
- Other layers for optical and electrical confinement in the structure for device operation
 - Efficiency and performance
- Blue, green, and red LEDs are used for full color displays

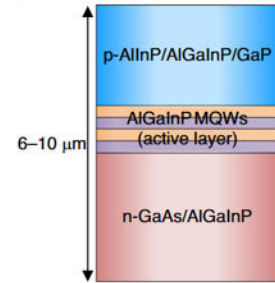
GaN-based LED



Nakamura et al., 1995

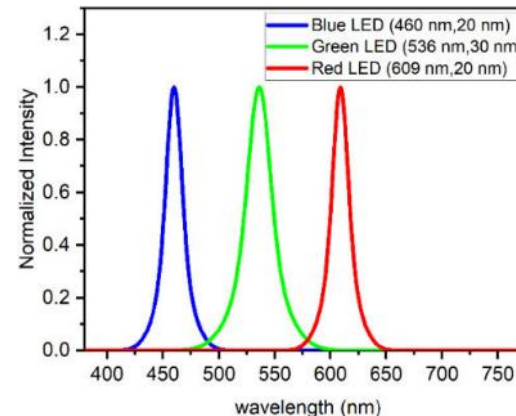
InGaN active region
Blue, green, red microLEDs
Sapphire or silicon substrate

AlInGaP-based LED



T.S. Kim et al., 2025

AlGaInP active region
Red microLEDs
GaAs substrate

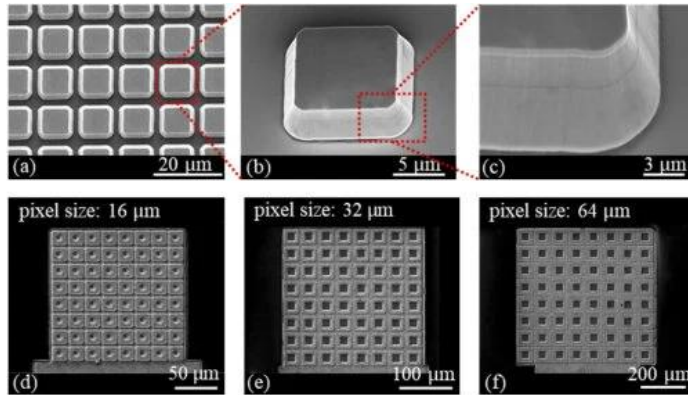


Z. Han et al.

Different Types of MicroLEDs

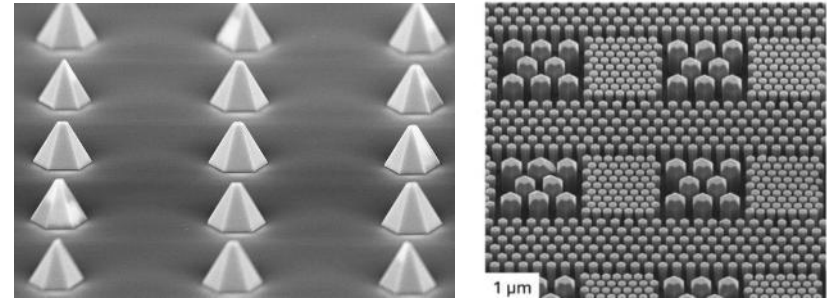
- Many types of microLEDs are emerging
- Two primary approaches

2D epi → etched microLEDs



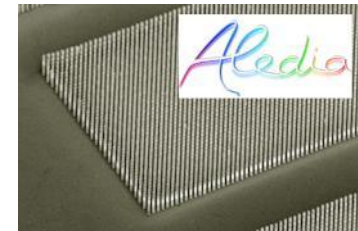
Y. Zhao et al.

Selectively grown nanowire or structured LEDs



Polar Light Technologies

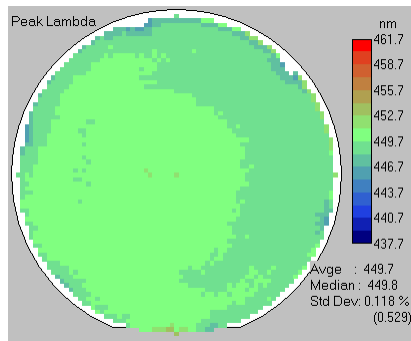
Aledia



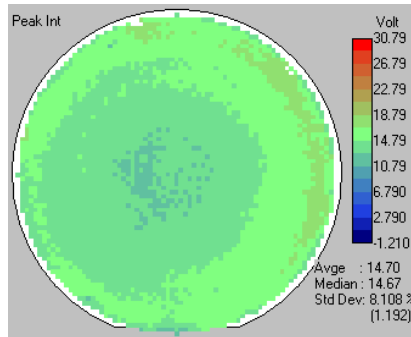
- Tradeoffs between epitaxy process complexity, wafer processing, and device performance

GaN PL Uniformity for Sapphire & Silicon Substrates

150mm Sapphire Wafer



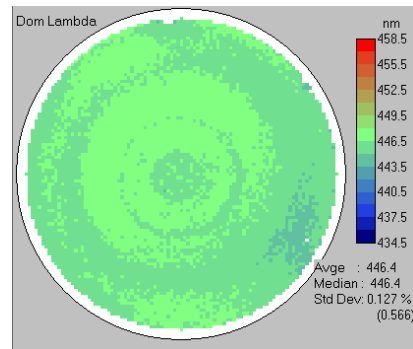
PL uniformity
 $1\sigma = 0.53 \text{ nm}$



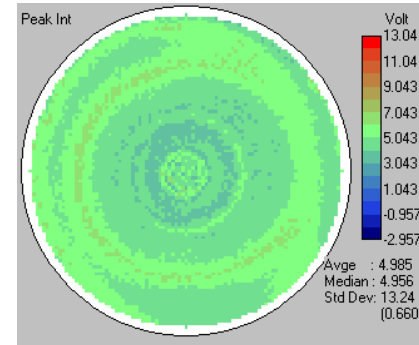
PL intensity
 $1\sigma < 15\%$

2mm EE

200mm Silicon Wafer



PL uniformity
 $1\sigma = 0.57 \text{ nm}^*$



PL intensity
 $1\sigma < 15\%$

*Allos collaboration

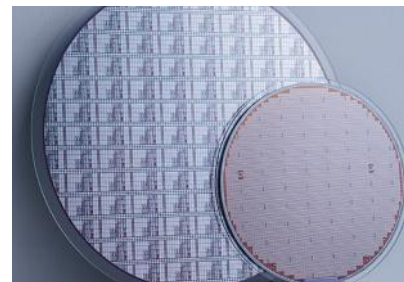
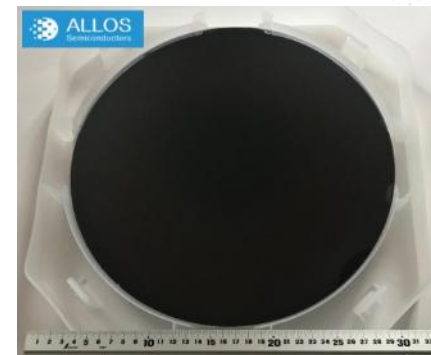
4mm EE

MicroLED on 300mm Wafers

- The silicon Semi industry operates at a scale enabling reduced technology cost
 - 300mm wafer
 - High-volume manufacturing
- 300mm manufacturing advantages
 - Advanced backplane technology for drivers
 - Efficient wafer utilization
 - Advanced node lithography and processing
 - Leveraging development for GaN power devices
- 300mm GaN-on-Si microLED devices are being developed to utilize this low-cost, scaled manufacturing platform

300mm GaN epi capabilities

- Multi-chamber cluster
- Fully automated

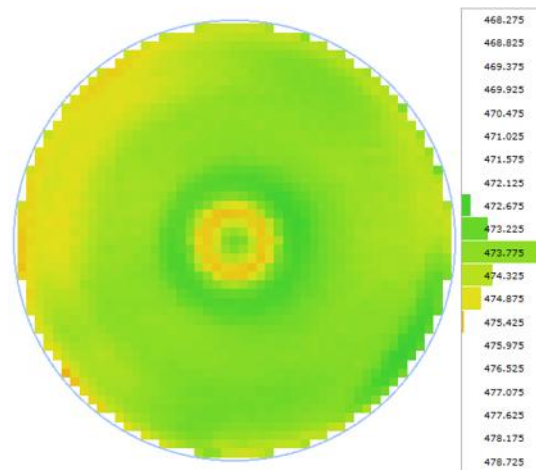


Infineon

Veeco

MOCVD of GaN MicroLEDs: 300mm Si Substrate

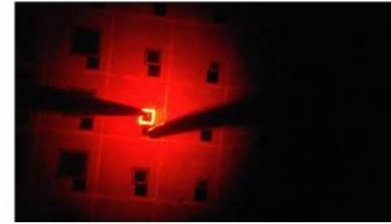
- System and process optimization has led to demonstrations of microLED epiwafers with full wafer uniformity < 1 nm
- Very promising for AR/VR and interconnect applications



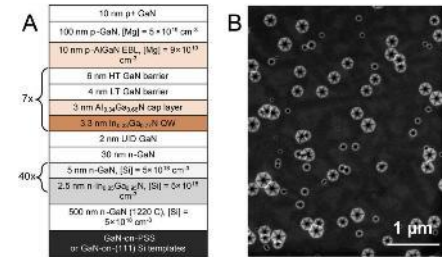
300mm GaN on Si
Wavelength: 474 nm
PL uniformity (1σ): 0.55 nm

Red GaN-based MicroLEDs

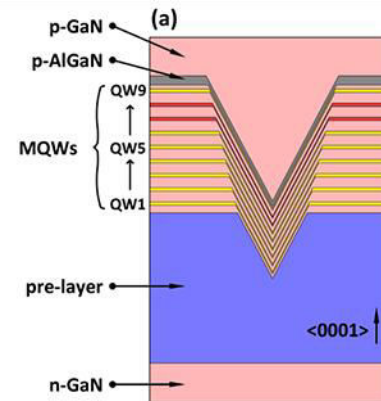
- Red emission from InGaN is challenging due to large required In concentrations
 - Lattice mismatch → layer strain (2D structures)
 - InGaN spinodal decomposition
- Limited efficiency due to challenges with material
 - Lower temperature growth for In incorporation
 - Superlattice structures used for stress engineering
 - Blue shift of emission with increasing current injection
 - Carrier injection behavior
- V-defect engineering for wavelength and efficient carrier recombination



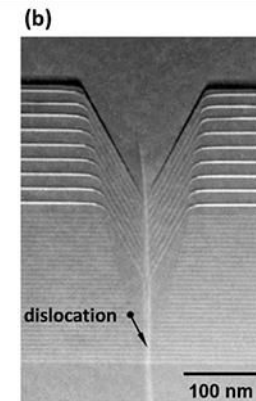
Soitec



J. Ewing et al.



S. Zhang et al.



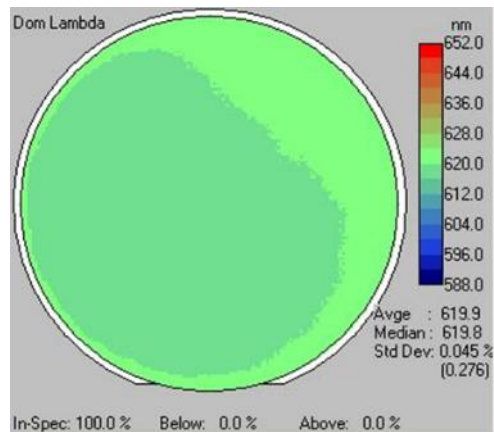
AlInGaP MQW Uniformity

- 25 pair MQW growth (60% AlInGaP/InGaP)
- 150mm wafer with 3mm EE
- PH3 flow = 2.5slm; 50nm/m

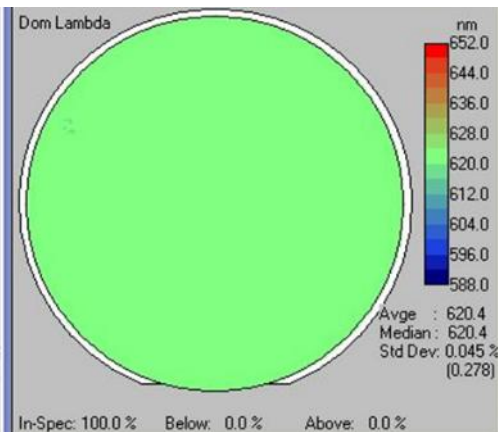
25 x	Material	Thickness (nm)
	GaAs cap	5
	Q100 clad	200
	Q60 SCH	77.5
	Q60 QB	7
	InGaP QW	5
	Q60 SCH	100
	Q100 clad	660
	GaAs buffer	

MQW (nm)	WiW Uniformity 1 σ
619.9	0.27nm
620.4	0.28nm
WtW Range: $\pm 0.25\text{nm}$	1 σ Uniformity: 0.28nm

Inner wafer



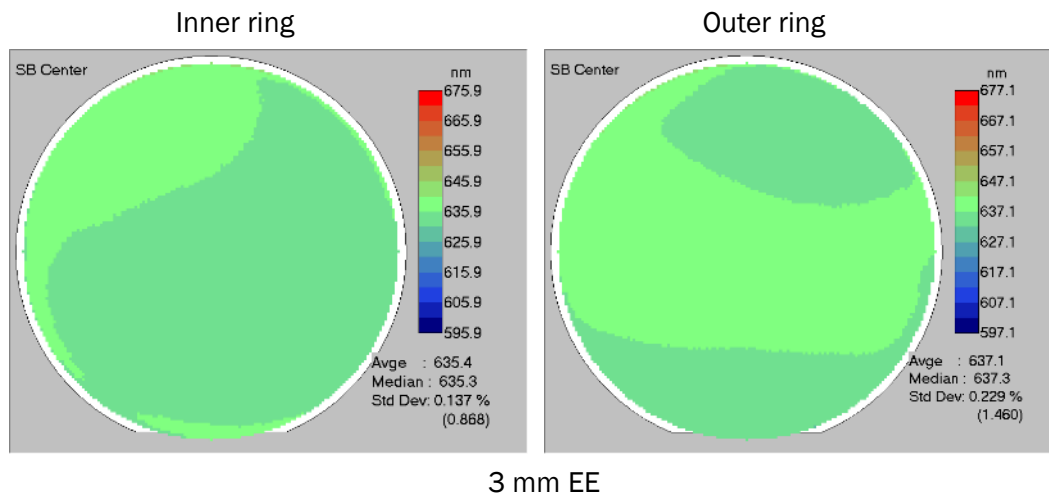
Outer wafer



Uniformity (1 σ) = 0.3nm demonstrated

AlGaAs DBR Uniformity

- AlAs/A50 DBR
 - AlAs growth rate = 90nm/min
 - A50 growth rate = 150 nm/min



DBR SB Center (nm)	WiW Uniformity (σ/x)
635.4	0.13%
637.1	0.23%
WtW Range: $\pm 0.8\text{nm}$	1 σ Uniformity: 0.18%

Average within wafer uniformity: 0.18% 1 σ /average

MQW Run-to-Run Repeatability

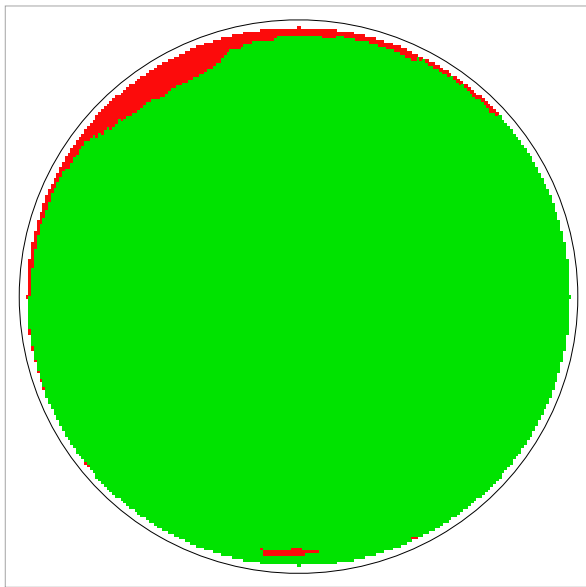


		MQW (nm)	WiW Uniformity 1 σ
Run 1	Inner	619.9	0.27nm
	Outer	620.4	0.28nm
Run 2	Inner	619.7	0.29nm
	Outer	620.2	0.25nm
Run 3	Inner	619.7	0.24nm
	Outer	620.2	0.26nm
		WtW Range: $\pm 0.35\text{nm}$	1 σ Uniformity: 0.27nm

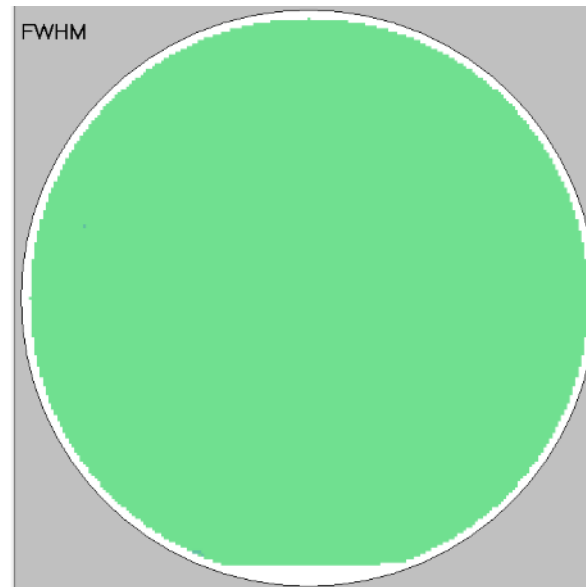
3mm EE

8" Red MicroLED Wafer Level Thickness and PL FWHM Uniformity

Thickness vs $\pm 1\%$ range = 97% with 3mm EE



FWHM < 4nm range = 100% with 3mm EE



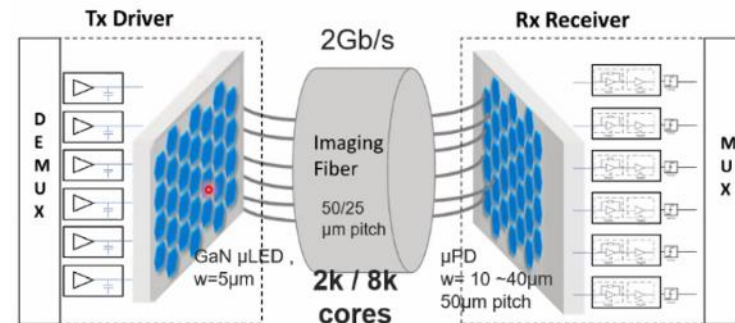
Highly uniform thickness and FWHM as required for MicroLEDs
demonstrated on 200mm wafers

MOCVD of MicroLEDs for Interconnects

- Ongoing development
- Compelling advantages for optical I/O
- Multiple alliances working on microLED systems
- Tier 1 system-level integration development
- Need Data Center roadmaps for the technology
- 2028 cited as starting deployment
- MOCVD
 - Epi capabilities demonstrated (blue microLED)
 - Optimize device structure for rapid modulation rate (> 1 Gbps)

MicroLED comparison to lasers for optical interconnects

Advantage	Disadvantage
Lower energy/bit (1 pJ/bit) Small size Si substrate for integration Lower cost compared to lasers Backreflection tolerance Lower temperature sensitivity	Non-coherent light source Absorption and dispersion of signal Non-collimated light source



CEA-Leti

Future Directions

- Continue to reduce epi costs for microLED displays
 - Larger wafer sizes → up to 300mm
 - Improve uniformity
 - Smaller edge exclusion
 - Higher throughput of growth systems
- Improve efficiency of small-size microLEDs
 - Some epi optimization; much of this is device processing
- Improve efficiency of red InGaN devices
 - Need > 4x improvement in efficiency
 - Stabilize wavelength across output power
- Continue development for optical I/O applications for AI computing
 - Higher device modulation rates: target 4 Gbps
 - Start commercialization with scale-up system integration

Summary

MicroLED applications

Growing opportunities in microLEDs for advanced display applications and optical interconnects for AI computing

Starting to see manufacturing for early-stage products

What is MOCVD

MOCVD is a growth technique for the creation of epilayers of semiconductor materials

Systems are designed to address the specifics of the material chemistry and epiwafer metrics for volume manufacturing

GaN and GaAs microLED epiwafers

Many epi technology needs are largely met for GaN and GaAs microLEDs

GaN microLEDs are grown on substrates up to 300mm to leverage Semi-type manufacturing

Red InGaN-based microLEDs remains challenging

Red AlInGaP-based microLEDs lead commercial applications today



MAKING A **MATERIAL** DIFFERENCE

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Thank You for
Your Attention!