“Green” LED Manufacturing
Enabled by MOCVD Technology

Dietmar A. Schmitz
AIXTRON SE
Vice President Corporate Technology Transfer

The Power of $x$
Outline

- Market overview and motivation
- MOCVD production technology of choice
- MOCVD “green” optimization strategy
- MOCVD Close Coupled Showerhead Technology
- Optimization
  - Reactor scaling/Capacity increase
  - Growth rate optimization
  - Process Control improvement
- Impact Analysis
- Outlook
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Will anyone living, live to see our little light burn out?
After 100 years of constant use, it may lose only half its brightness.
That’s because we don’t use a bulb, a filament or a vacuum.
We use a tiny crystal chip called a light emitting diode. It works something like a transistor, but let’s not get into all that.
Our diodes are already in use on computer panels, freeing the man who used to look for burned-out bulbs among all those hundreds of winking lights.

That’s a good market. But let’s look at markets to come. How about a flat head-light as wide as your car, to evenly light the road? Or an inch-deep color TV set? Or a wrist watch without a dial, that shows the time in numbers at the instant you push a button?

That’s part of the future we see in our crystal chips. And just a small part of the future we see in **Monsanto: the science company.**
Solid State Lighting in 2012

... are where we want to be?
Required Cost Reduction of Packaged LEDs (US Department of Energy July 2011)

- Substrate
- Epitaxy
- Wafer Processing
- Phosphor
- Packaging

2010: Epi
2012
2015
2020

10x reduction
The Global SSL Industry’s Challenge

SSL implementation is just starting
Market development is difficult to be predicted
Will very much depend on LED cost and performance
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Principle of (LP-)MOCVD(VPE)

\[
\text{Ga(CH}_3)_3 + \text{AsH}_3 \rightarrow \text{GaAs} + 3\text{CH}_4
\]

\[
\text{Ga(CH}_3)_3 + \text{NH}_3 \rightarrow \text{GaN} + 3\text{CH}_4
\]

- Gas blending
- Reactor
- Scrubbing system
- Vacuum pump
- Throttle valve
- Filter unit
- High purity, precise mixing
- Crystal quality, thickness uniformity, reproducibility
- Safety
- Production oriented
- Low cost of ownership

GaAs, InP, sapphire substrate, T \( \sim \) 400 - 1200°C
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Typical Basic LED Structure

- 20 nm p+GaN
- 170 nm pGaN
- 25 nm pAl$_{0.15}$Ga$_{0.85}$N
- 16 nm GaN QB:
- 2.7 nm In$_{0.16}$Ga$_{0.84}$N QW
- 16 nm GaN QB:
- 2.7 nm In$_{0.16}$Ga$_{0.84}$N QW
- 16 nm GaN QB:Si
- 2.7 nm In$_{0.16}$Ga$_{0.84}$N QW
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- 16 nm GaN QB:Si
- 2.7 nm In$_{0.16}$Ga$_{0.84}$N QW
- 16 nm GaN QB:Si
- 0.1 µm GaN:Si (< 1e18)
- 2 µm GaN:Si (6e18)
- 0.2 µm GaN
- 1.4 µm GaN
- 0.6 µm GaN
- 30 nm GaN nucl.
- Sapphire
Stages for MOCVD Process Optimization

- MOCVD Technology requires high process temperatures. Most of the required heat is disposed in cooling loops
- **Different approaches to conserve electrical energy are possible**
- For the production of LEDs raw materials of limited availability and difficult preparation are required (e.g. Ga, In). Large amounts of purified gases (H₂ and NH₃) are also necessary
- **Smart management of natural resources is advised**
- Waste is generated by unused raw materials and not usable product
- **Optimization of process efficiency and yield is necessary to control**
Approaches to save resources

• 3 ways to conserve the resources mentioned above

• Upscaling of the MOCVD reactor chamber

• Geometrical optimization of gas injection and wafer arrangement (reactor fill factor) improving efficiency and yield

• Reduction of total process cycle time (through high growth rates and fast temperature control)

• The approach is demonstrated at the example of the Close Coupled Showerhead tool CRIUS®
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Close Coupled Showerhead Reactor (3x2” History)
Close Coupled Showerhead Reactor

- 3D Uniform gas Injection
- \( \Rightarrow \) patented dual plenum showerhead
- Injection into boundary layer
  - jets relax overlaying close to surface
  - depletion decoupled from radial flow
- Thermally stable controlled showerhead

Computed MO species distribution in a close coupled showerhead reactor
Close Coupled Showerhead Reactor (Model)

NH3 Injection

- No cross talk between MO and alkyl orifice injection
- True two flow injection
- Reduced risk for adduct formation

TMGa Injection
Showerhead Detail

100 tubes/inch\(^2\)

\(\varnothing_{\text{tube}} = 0.6\text{mm}\)
CCS reactor scale up (Model)

CCS 6x2“
MMGa molar concentration
Normalised to inlet molar fraction

CCS 19x2“
MMGa molar concentration
Normalised to inlet molar fraction

CCS 30x2“
MMGa molar concentration (normalized to inlet molar fraction)

Application of chemical boundary layer theory the same for all configurations (precursor decomposition identical).

Simple scale up of reactor chamber and process.
Process behaviour is the same for all reactor configurations.
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MOCVD evolution
Chamber Upscaling

... and equivalent 4” and 6” capacities
Geometrical Reactor Upscale

Same chamber size! Pure geometrical wafer load optimization

2010

July 2011

today

Substrate rearrangement

Susceptor area increase

CRIUS® II-L

CRIUS® II-XL
Blue MQW Wavelength Uniformity
CRIUS®

Average = 459.7 nm
w-2-w σ = 0.85 nm
On-w σ = 1.4 nm
Blue MQW Wavelength Uniformity
CRIUS® II

Average = 452 nm
w-2-w $\sigma$ = 1.0 nm
On-w $\sigma$ = 1.4 nm
Blue MQW Wavelength Uniformity
CRIUS® II-XL

Average = 452.3 nm
w-2-w σ = 0.90 nm
On-w σ = 1.42 nm
MOCVD > 6 inch The ultimate step

200 mm / 300/ 450 mm MOCVD is feasible!

„Silicon-style“ technology
Impact of reactor size and capacity

• Upscaling the active growth area increases chamber size to a certain point.

• The electrical supply and cooling capacity required does scale sublinear with the area increase.

• Consequently the consumption is reduced by the sublinearity

• Pure geometrical capacity increase by rearrangement does not increase required supplies!
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MOCVD technology trend: high growth rates
CRIUS II-XL

up to 32µm/h

Very high growth rates

„classical“ process regime
Impact of growth rate maximization

- The maximization combined with efficiency gain (specifically when doing geometric upscale) can lead to a significant chance to reduce process time

- Consequently power, cooling and non-active gas consumption is reduced

- Improved efficiency leads to resource conservation on the raw materials for epitaxial growth
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Advanced metrology

- MOCVD growth on large substrates requires management of wafer bow → in situ curvature measurement
- Feed back / close loop control of reactor temperature
- Measurement and control of individual wafer temperature
- In line metrology
ARGUS Topside Temperature Control
Key Features

- Eliminate Temperature Variation
  - Within each run → Wafer-to-Wafer
  - Run-to-Run → High Yield
  - Hardware → NO-BAKE

- Increased reproducibility and yield

- Simplified recipes by automated zone balancing to achieve best uniformity

- Enhanced control on the vital parameter temperature allows process time optimization in temperature steps (QW growth)
Top Side Temperature Control

- Closed Loop – Live – Heater Zone Control
- Ultimate Ring-to-Ring & Run-to-Run Wavelength Stability

Applicable Add-on to All CRIUS® II Series
Impact of yield improvement

- The enhanced control capability allows the optimization in process time by eliminating unspecific stabilization times and controlling process temperature on the spot for the chemical reaction.

- Reduced process time leads to conservation of energy and non active gases. Eventually raw materials as well as the flow of those is usually not interrupted during stabilization times but rather discarded in Vent flow.
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Analysis of Optimization

In the following the effect of the described optimization on various consumables is evaluated.

The described optimizations are based on the following path:

- Reference Standard CRIUS® reactor
- Chamber size increase to CRIUS® II
- Susceptor size increase to CRIUS® II-L
- Geometrical optimization of susceptor use on CRIUS® II-XL
- Process cycle time optimization in CRIUS® II-XLC
Optimization of Power and Cooling Efficiency

- Energy conservation by reactor upscaling
- A reduction of almost 50% is achieved compared to the reference
- Cooling water is accounted as energy equally seriously
Gain of optimization on resource efficiency

- The conservation of raw material resources is strongest in the geometrical improvement steps.

- Interestingly the cycle shortening is most significant for the TMIn.
Gain on non active gas consumption

Hydrogen Consumption per 4" Wafer (m³)
Validated Gain on Entire Consumables

- The overall effect is depicted in the consumption cost reduction as an economically important factor aside with the resource conservation aspect.
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MOCVD has a large potential for a more efficient utilization of required resources. In particular gases, metal organics, electricity and water can be significantly saved. AIXTRON’s CRIUS II-XL platform offers the industry’s most comprehensive portfolio of resource-saving technologies. A straight forward scale-up from CRIUS to CRIUS II and CRIUS II-L already offered a major opportunity for savings. The more recent introduction of CRIUS II-XL allows exploiting the potential of an optimization of the reactor geometry. Finally, as the latest improvement, a combination of uniquely high growth rate and fast temperature control increases the overall resource efficiency of the CRIUS II-XL reactor once more.
Our common target – revolutionize lighting

Being ahead of roadmap targets
Conserve Energy world Wide!
Reduction in Energy Consumption by SSL

- LED lighting reduces Energy consumption by 75% compared to traditional technology (Energy Star 2011)
- Energy consumption by illumination in Germany:
  ~79.848 GWh (AG Energiebilanzen)
- Equivalent of power stations economized through replacement by SSL:
  - 10 Coal fired Power Plants (equiv. Nuclear Power Plants)
  - 59.8 mio to CO$_2$/year
- World wide power consumption for illumination:
  2.700.000 GWh (18% of total el. Power)
  - Economization potential 2.025.000 GWh
  - Several hundred power plant blocks!
Operation of 9 State of the art MOVPE Reactors 
Economizes 1 Power plant Block/year
Thank you for your attention

Dietmar A. Schmitz
Vice President Corporate Technology Transfer
d.schmitz@aixtron.com

AIXTRON SE
Kaiserstr. 98
52134 Herzogenrath
Germany

www.aixtron.com