Considerations Towards a Nitride Semiconductor Substrate Roadmap

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Abstract

We present a comparative substrate analysis for use in GaN/InGaN LED manufacturing that is focused on bare sapphire, PSS sapphire, AlN templates on sapphire, GaN templates on sapphire, and bulk GaN, with respect to their ability to support the continuous need for lower cost and higher performance LED devices. LED market value creation estimates are presented based on the predicted impact of each substrate approach on wafer level device yield and brightness, epitaxial process cycle time, capital equipment costs and manufacturing footprint per unit output. Further consideration of substrate approach maturity leads us to propose a nitride semiconductor substrate adoption roadmap for high brightness LEDs suitable for solid state lighting.

INTRODUCTION

Nitride semiconductor devices are enjoying explosive commercialization for applications based on blue, green, and white LEDs, as well as ultraviolet (UV) detectors and violet laser diodes. New applications are opening up including those based on UV LEDs, power switching devices, and high frequency electronics. Additionally, several new devices are in the R&D stage such as terahertz emitters and quantum cascade lasers. The market for nitride semiconductor devices today is above $12B and is expected to surpass $60B over the long term.

Accompanying the commercialization success of nitride semiconductor devices is the continuous drive to reduce device cost and improve performance. Historically the question of what substrate to use for high brightness blue and green LEDs was simple to answer: sapphire or silicon carbide (SiC). Today Aluminum Nitride (AlN) and Gallium Nitride (GaN) substrates in both bulk and template form are becoming available, and determining the best substrate approach requires a complex analysis of substrate cost and size, as well as several other factors, including the impact on device manufacturing yield, throughput, and other factors. Table 1 contains a partial list of parameters that are important for LED device manufacturers. Maximizing benefits while simultaneously considering the timeframe of availability of the technologies discussed allows one to produce a reasonable nitride semiconductor substrate roadmap.

Table 1 - Some Critical Nitride Substrate Parameters

Wafer and Epitaxy Cost	
	Substrate cost / substrate availability
	Epitaxy growth cost / epi-wafer value
Post-Epitaxy Processing Cost	
	Post epitaxy processing cost / processed wafer value
	Overall process cost / overall LED value
	Capital equipment cost
	Manufacturing footprint
	LED Margin / Profit
Performance and Yield	
	Process yield – LED brightness
	Process yield – LED wavelength
	Process yield – overall
Future Proofing and Future Flexibility	
	Process equipment scalability
	Wafer size scalability
	Intellectual property availability and/or protection
	Ease of integration with future technologies

MARKET AND TECHNOLOGY STATUS

LED manufacturers traditionally focus on ever-increasing LED brightness with an ultimate goal of creating a viable multi-billion dollar solid state lighting market. Even with this tremendous focus on LED brightness, according to a recent market status presentation[1], more than 65% of 2010 sales revenue and 95+% of the LED unit volumes (derived by applying reasonable device size and price assumptions) remain in the lowest segment of the LED brightness scale (below 10 lumens). There is therefore tremendous headroom available to improve the overall value of most LED processes still being run today.

With regard to substrates, most high-brightness GaN LEDs today are produced on 2” and 4” diameter sapphire substrates, using high volume MOCVD production tools. Sapphire based LED growth requires that the MOCVD growth run can be as long as 10 hours and involves much more than growing the device active region: over 50% of the MOCVD cycle time is spent on pre-treating, heating, cooling, growth interrupts, temperature ramps, and the growth of both undoped and n+ doped GaN buffers or other buffer layers.

The complexity of the MOCVD process, in particular the use of temperatures that vary by as much as 600°C during the different growth steps, results in poor overall process uniformity and overall LED yields that require binning in order to provide customers with batches of LED that have similar brightness and color. LEDs that do not make the prime-grade, ultra-high brightness, $5 per LED bins are relegated to lower bins and command lower revenue, perhaps only $0.01 per LED or even lower.

A NITRIDE SUBSTRATE ROADMAP

In this section, we will evaluate and compare the relative advantages, disadvantages, and overall value of the current sapphire based processes against the dominant substrates being discussed for future adoption, namely PSS sapphire, AlN on sapphire templates, GaN on sapphire templates, and bulk (free-standing) gallium nitride substrates. Figure 1 shows LED wafer layer schematics. Recent efforts have focused on silicon as a potentially viable substrate that is garnering interest for LEDs; however the efficiency and/or brightness remains 5-10x lower than LEDs available on the market today[2], so we will not address silicon at this time. Regarding AlN and GaN templates on sapphire, we consider an MOCVD based template solution to be largely equivalent to the current MOCVD processes that are already being run, and will therefore also not address AlN and GaN templates being grown on obsolete MOCVD systems. Instead, we will include analysis of AlN templates grown via Plasma Vapor Deposition of NanoColumns (PVDNC) and GaN templates grown by Hydride Vapor Phase Epitaxy (HVPE). Both template methods are less costly, faster, and have higher purity than traditional MOCVD growth and are therefore viable alternatives for adding significant value to the LED manufacturing chain.

Kyma's customers have provided data showing how the substitution of a PVDNC AlN template on sapphire for the traditional GaN process nucleation layer results in a 5 to 15% increase in LED brightness, a 50 to 70% defect density reduction, and a simultaneous improvement in wavelength binning. These results span a range of very different high-volume customer processes and further improvements with process optimization are expected in the near future. Additionally, it is notable that similar benefits have been observed for PVDNC AlN deposited upon patterned sapphire substrates (PSS) relative to using PSS alone. Therefore we propose PVDNC AlN templates as the first step in our substrate adoption roadmap as they are a clear value add to existing sapphire and PSS sapphire substrates.

Kyma's own experience shows that the AlN template can nucleate high-quality GaN growth without traditional 2-step 2-temperature buffer layers. When the AlN template is combined with HVPE growth of GaN, which is inherently cleaner, faster, and less costly than MOCVD growth of GaN,

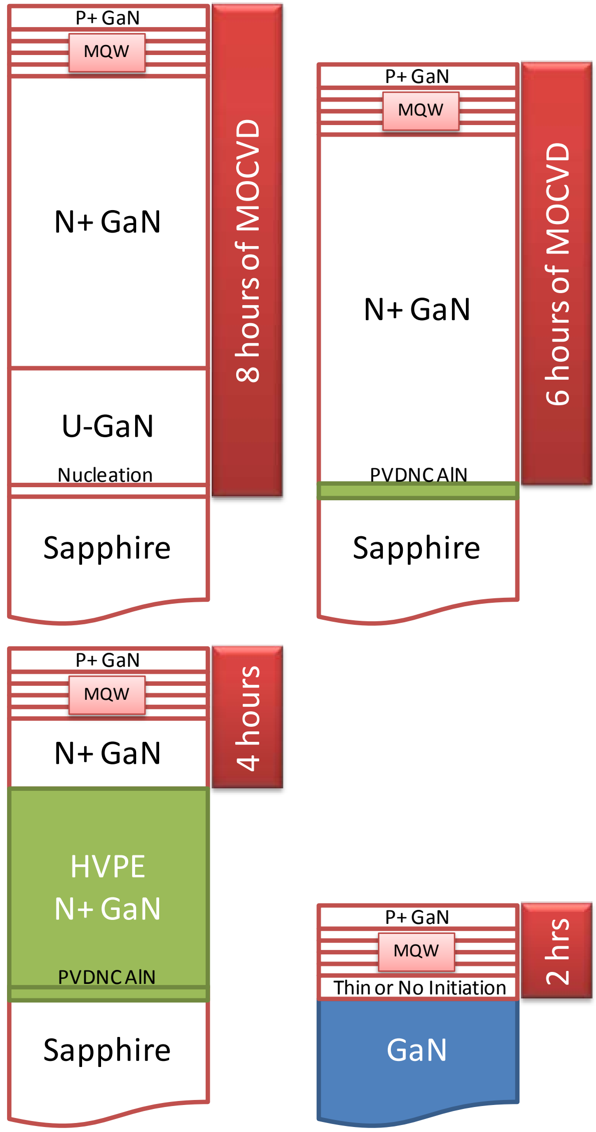

Figure 1 - Comparison of Sapphire (top left), AlN template (top right), GaN template (bottom left) and Bulk GaN (bottom right) processes

this produces a GaN template that offers an additional reduction in defect density above what the AlN template alone offers for LED manufacturing. The expected 25-35% increase in GaN thermal conductivity[3] that results from the order of magnitude reduction in defect density means better thermal uniformity during subsequent MOCVD active layer growth, which should boost the yield in terms of wavelength and brightness binning, and should support less efficiency droop in the resulting devices that will operate cooler than high defect density devices. HVPE-produced GaN templates are therefore the second step in the progression along our substrate roadmap, with the transition happening during the next 3-5 years.

Compared to templates and sapphire alone, bulk GaN is expected to support even faster MOCVD cycle times, even higher thermal conductivity, and good vertical contacting, all supporting better, faster, and cheaper devices with the notable exception that GaN substrate availability in volumes suitable for commercial LED manufacture (>10,000 2" equivalent per month) is still several years away.

A summary of the relative positions of each substrate over time is presented in Table 2. This extended abstract cannot detail all of the reasoning behind the various rankings, however the general trend for adoption preference is from left to right in the table over time.

Table 2 - Substrate Options Metrics "Today / In 3-5 Yrs / In 5-10 Yrs" (1 = Best at the Time, 5 = Worst at the Time)

	Bare Sapphire	PSS Sapphire	AlN Template	GaN Template	Bulk GaN
Substrate cost & availability	1/1/1	2/2/2	3/3/3	4/4/4	5/5/5
Epitaxy growth cost	5/5/5	4/4/4	3/3/3	2/2/2	1/1/1
Wafer and Epitaxy Total	6/6/6	6/6/6	6/6/6	6/6/6	6/6/6
Post epitaxy processing cost	1/1/4	3/3/3	2/2/2	4/4/1	5/5/5
Capital equipment cost	4/4/5	3/3/4	1/2/3	2/1/2	5/5/1
Manufacturing footprint	3/4/5	2/3/4	1/2/3	4/1/2	5/5/1
Post-Epi Processing Total	8/9/14	9/9/11	4/6/8	8/6/5	12/15/7
LED Margin / Profit	3/4/5	2/3/4	1/2/2	4/1/2	5/5/1
Process yield – LED brightness	3/5/5	2/4/4	1/2/3	5/1/2	4/3/1
Process yield – LED wavelength	5/5/5	4/4/4	3/3/3	2/2/2	1/1/1
Performance and Yield Total	11/14/15	8/11/12	5/7/8	11/4/6	10/9/3
Process equipment scalability	3/4/5	2/3/4	1/2/3	4/1/2	5/5/1
Wafer size scalability	1/1/1	2/3/3	3/2/2	4/4/4	5/5/5
Intellectual property availability and/or protection	1/1/1	4/4/4	2/2/2	5/5/5	3/3/3
Ease of integration with future technologies	4/4/4	5/5/5	2/3/3	3/2/2	1/1/1
Future Proofing Total	9/10/11	13/15/16	8/9/12	16/12/13	14/14/10
Ranking Today	2	3	1	4	5
Ranking In 3-5 Years	4	3	1 (tie)	1 (tie)	5
Ranking In 5-10 Years	5	4	3	2	1

Value Creation

While we are not in a position to calculate the exact dollar value differences between substrate approaches for specific LED manufacturer processes, it is instructive to estimate the magnitudes from an overall market perspective in order to understand the significant financial driving forces that will push the substrate roadmap forward. The results of our value calculations are presented in Table 3. The calculations themselves are proprietary and approximate; however the magnitudes are so substantial that we are comfortable that even with errors in our assumptions, the conclusions are still valid. The calculations include considerations of yield, wafer size, die sizes, process costs, LED sales pricing, and a current industry wide run rate of 2 million 2" equivalent wafers per month.

Table 3 – LED industry value creation by moving to next generation substrates

	AlN Templates	GaN Templates	Bulk GaN
Per +5% Prime Spec wavelength and brightness binning yield	$1,440M	$1,440M	$1,440M
Increased throughput	$700M	$2,150M	$8,600M
Facility expansion cost savings	$60M	$180M	$1,200M
Total Annual Savings	$2,200M	$3,770M	$11,240M
Reduced Cap-ex (one-time savings)	$1,200M	$825M	$4,800M

Conclusions

A nitride substrate roadmap has been presented that uses a number of technical, financial, and business considerations to rate and rank the top substrate contenders for the LED industry over the next decade. The current trend of sapphire wafers moving to PSS sapphire is validated, and then future progression to PVDNC AlN templates on sapphire, HVPE GaN templates on sapphire, and eventually ending with full market maturity using bulk GaN substrates. Results from a value proposition model are presented showing creation of between $3.4 and $16 billion in LED industry value that provides the driving force for change from the status quo.

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References

[1] Yole Developpement presentation at Semicon West 2010

[2] ICNS-8, Session H: Epitaxial Growth I, L_1006: "High power InGaN LEDs grown on Si substrate by MOCVD", October 18- 23, 2009, ICC Jeju, Korea.

[3] C. Mion, J.F. Muth, E.A. Preble, and D. Hanser, "Accurate dependence of gallium nitride thermal conductivity on dislocation density," Appl. Phys. Lett. 89 (2006) 092123.

Acronyms

AlN: Aluminum Nitride
GAN: Gallium Nitride
HVPE: Hydride Vapor Phase Epitaxy
INGAN: Indium Gallium Nitride
LED: Light Emitting Diode
MOCVD: MetalOrganic Chemical Vapor Deposition
PSS: Patterned Sapphire Substrate
PVDNC: Plasma Vapor Deposition of NanoColumns
UV: Ultraviolet