To understand the current pricing environment and try to predict future trends, it is necessary to look back at the previous price cycle:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial conditions</strong></td>
<td><strong>Trigger</strong></td>
<td><strong>Short Term Effect</strong></td>
<td><strong>Mid Term Effect</strong></td>
<td><strong>Long Term Effect</strong></td>
</tr>
<tr>
<td>Worldwide Economic Crisis</td>
<td>LED TV: strong demand hike</td>
<td>Sapphire Shortage</td>
<td>Excess Investment</td>
<td>Price crash + long depression</td>
</tr>
</tbody>
</table>

- Few sapphire makers
- World economic crisis affecting all industries
- Most sapphire makers cash strapped and unable to invest in new capacity.

Unanticipated\(^1\) and strong demand jump due to success of first LED TV models

- Material shortage $\rightarrow$ Dramatic material price increase (5x)
- High profits for established vendors and new entrants, regardless of cost structure

- Excessive capacity investments (also by anticipation of general lighting applications growth)
- More than 80 new companies trying to enter the market

\(^1\): Massive adoption of LED for LCD TV backlight wasn’t anticipated before at least 2010-2011

Excess capacity and slower than anticipated demand triggers price crash (8x drop)
Sapphire Core and Wafer Revenue
Top 20 Companies

Core and Wafer Revenue

Total: US$XXX m

- The top 5 vendors captured 35% of revenue. The top 20 captured 77%.
- The 65 remaining companies shared wafer related revenue of US$XXX m
- However, some of those “2nd tier” are quite successful with non wafer products. We estimate that those “other applications” totaled US$XXX m in 2013.
- PSS foundries entered the top 20 for the first time (Rigidtech, LGS, Aceplux)
There are two major candidates: Silicon and GaN. Both aim at displacing sapphire by improving LED cost of ownership (Lumen/$). However, the philosophy behind them is different:

- **GaN wafers** would significantly increase epiwafer manufacturing cost but enhance performance (light emitted by unit of chip surface) to levels that would still improve the Lumen/$ figure over sapphire.

- **Silicon** would deliver LED performance similar to sapphire but allow significant cost reduction at the die level by enabling manufacturing in existing, fully depreciated 8” CMOS fabs.

**Manufacturing Efficiency**
- Higher equipment throughput and yields
- Economy of scale

**LED Performance**
- Higher efficiency (lumen/W)
- More light per chip (driving current)

**GaN-on-Si LEDs** → Reduce component cost

**GaN-on-GaN LEDs** → Improve performance to reduce number of packages per System
# GaN on GaN LEDs

## Potential applications (General Lighting)

<table>
<thead>
<tr>
<th>Illustration</th>
<th>MR16, Spot</th>
<th>A19, Bulbs</th>
<th>Downlight</th>
<th>Troppher, Linear fluorescent</th>
<th>Streetlight</th>
<th>High Bay</th>
<th>Decorative</th>
</tr>
</thead>
</table>

### Requirements

<table>
<thead>
<tr>
<th>Illustration</th>
<th>MR16, Spot</th>
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<th>Downlight</th>
<th>Troppher, Linear fluorescent</th>
<th>Streetlight</th>
<th>High Bay</th>
<th>Decorative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small form factor, high density of light, focused beam</td>
<td>High volume</td>
<td>Directional beam pattern</td>
<td>NA</td>
<td>High flux required, Controlled beam shape for roadway lighting</td>
<td>High flux required, controlled beam shape</td>
<td>Design flexibility</td>
<td></td>
</tr>
</tbody>
</table>

### Challenge

<table>
<thead>
<tr>
<th>Illustration</th>
<th>MR16, Spot</th>
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<th>Streetlight</th>
<th>High Bay</th>
<th>Decorative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Management</td>
<td>Omni directional beam pattern, low glare</td>
<td>NA</td>
<td>Very large surface, diffused light, requires low glare</td>
<td>Priority is often to maximize energy efficiency rather than initial cost</td>
<td>Energy efficiency is important for total cost of ownership</td>
<td>Low glow usually preferred over high flux</td>
<td></td>
</tr>
</tbody>
</table>

### Comment

<table>
<thead>
<tr>
<th>Illustration</th>
<th>MR16, Spot</th>
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<th>Streetlight</th>
<th>High Bay</th>
<th>Decorative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal application for GaN. Currently no satisfying solutions for 50W MR16</td>
<td>Glare and cost of ownership are limiting</td>
<td>Can also be build with cost efficient Chip On Board (COB) LEDs</td>
<td>More suited for low/mid power LEDs</td>
<td>GaN could compete when initial cost is key</td>
<td>Solutions based on COB or standard power package already exist</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

### Opportunity for GaN

<table>
<thead>
<tr>
<th>Illustration</th>
<th>MR16, Spot</th>
<th>A19, Bulbs</th>
<th>Downlight</th>
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<th>Decorative</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Simulations were conducted for various 4” GaN wafers price and yield hypothesis in order to estimate the breakeven point with current sapphire based technology. The reference target point is represented by the current cost efficiency of a Flip Chip die built on a 4” Patterned Sapphire substrate.

Under those assumption, the breakeven point is <$XXX. We therefore consider that unless the price of 4” GaN wafer reaches this <$XXX target, adoption of GaN on GaN will be restricted to niche markets where the specific performance advantages of GaN (high flux over a small surface) overcome the price handicap.

An engineered substrate behaving like a GaN bulk wafer but offered at <$XXX would rapidly offer significant cost of ownership benefits over sapphire and could capture significant market shares.
LED Makers Positioning

Development status

Volume Manufacturing

Ramping Up

Pilot

R&D

No interest / Exited

Defensive

Core Strategy

LED makers committed to Si as differentiating technology

Established LED makers with strong sapphire-based technologies and no internal CMOS fab capacity

Established LED makers with limited differentiation on sapphire platform and access to internal CMOS fab → Strong incentive for Si

LED startups committed to Si as differentiating technology

Established LED makers with strong sapphire-based technologies and no internal CMOS fab capacity. Have experimented but ruled out Si in the short/mid term.
Cost Simulation Results

The simulations show a potential **cost reduction of -38 to 45% at the die level vs. a 4” sapphire vertical LED:**

### Die Cost break down

<table>
<thead>
<tr>
<th></th>
<th>Back End 0 Cost</th>
<th>Front End Cost</th>
<th>Raw wafer cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2” Sapphire Vert LED 1mmx1mm Probe 70%</strong></td>
<td>$0.053</td>
<td>$0.102</td>
<td>$0.008</td>
</tr>
<tr>
<td><strong>4” Sapphire Vert LED 1mmx1mm Probe 70%</strong></td>
<td>$0.035</td>
<td>$0.065</td>
<td>$0.006</td>
</tr>
<tr>
<td><strong>8” Si Vert LED 1mmx1mm Probe 70%</strong></td>
<td>$0.022</td>
<td>$0.039</td>
<td>$0.004</td>
</tr>
<tr>
<td><strong>8” Si Vert LED 1mmx1mm Probe 70% 4.5h MOCVD cycle</strong></td>
<td>$0.020</td>
<td>$0.033</td>
<td>$0.004</td>
</tr>
</tbody>
</table>

**Notes:**

- Front End = epitaxy + Si carrier preparation + wafer processing + bonding + epi substrate removal
- Back End 0 = Probe test + scribing → include yield costs (cumulated cost of all the rejected die)
Total MOCVD capacity increased 270% in the last four years, with China taking the lead since 2012. However, we estimated that only 70% of the reactors present on Chinese soil are operating.

**2010 - 2014 MOCVD Capacity Evolution**

**Note:** based on physical location of the reactors (i.e.: reactors at Chinese branches of Taiwan based LED makers are counted in China)
Wafer Diameter Trends: Geographic Breakdown

Q1-2014 Diameter Breakdown per Region

See comments next page.
The PSS supply chain is **highly fragmented** with multiple players and **products moving along 5 different possible channels**:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sapphire Maker → PSS Foundry → LED Makers</td>
</tr>
<tr>
<td>2</td>
<td>Sapphire Maker with internal PSS capabilities → LED Makers</td>
</tr>
<tr>
<td>3</td>
<td>Sapphire Maker → LED Makers with internal PSS Capabilities</td>
</tr>
<tr>
<td>4</td>
<td>Sapphire Maker → PSS Foundry → LED Makers</td>
</tr>
<tr>
<td>5</td>
<td>Sapphire Maker → PSS Foundry → LED Makers</td>
</tr>
</tbody>
</table>

Sub-contracting occurs in channels 4 and 5.
PSS adoption rates vary by region with China, Korea and Japan leading with more than XX%, followed by Taiwan at XX%.

US and Europe are trailing at XX% and XX% respectively due to the prevalence of vertical LED structures amongst the local LED makers. However, Philips Lumileds (US) started using small volumes of PSS in 2013.
PSS Capacity In Taiwan

Overview

Note: all capacities in TIE per month

Q1 2014 PSS Capacity

Taiwan

Total Volume Processed internally by LED makers: xxk TIE
• XXX is the only Taiwan based LED maker that processes a large fraction of its PSS needs internally.

Total Capacity: xxk TIE
• Leading foundries are: Rigidtech, XXX, XXX and XXX.
• Multiple smaller foundries have emerged during the PSS shortage in 2012. We believe that most could disappear in the next 12-18 months.

Total Capacity: xxk TIE
• Most sapphire makers are now vertically integrated and have some internal PSS capacity.
• Leaders are: Crystalwise, Crystal Applied Technology, Tera Xtal (ACTC), Procrystal.
• Following the merger with SAS, Crystalwise is now the largest PSS producer with a total capacity of 350k.
• Crystal Applied Technology has been outsourcing PSS to foundry partner XXX but is now setting up in-house capacity in China.
Evolution of Peregrine Ultra CMOS Technology

- **STeP2**: 500 nm. Epi on 6” Sapphire
- **STeP3.5**: 350 nm. Epi on 6” Sapphire
- **STeP4**: 350 nm. Epi on 6” Sapphire
- **STeP5**: 350 nm. Bonded on 6” Sapphire
- **STeP8**: 250 nm. Bonded on 6” Sapphire
- **STeP10**: 130 nm Epi on 8” eSI-SOI

Production Release Year:
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014

RonCoff: 768
- **STeP2**: 500 nm. Epi on 6” Sapphire
- **STeP3.5**: 350 nm. Epi on 6” Sapphire
- **STeP4**: 350 nm. Epi on 6” Sapphire
- **STeP5**: 350 nm. Bonded on 6” Sapphire
- **STeP8**: 250 nm. Bonded on 6” Sapphire
- **STeP10**: 130 nm Epi on 8” eSI-SOI
The TIE metric was a convenient way to gage and compare capacity from one vendor to another. However, it is not applicable to non-wafer products like cell phone display covers and other shapes:
- Square shapes lead to potentially higher utilization rates
- Different orientations possible

The example below illustrates how for a boule with a given geometry, the potential material usage varies depending on the geometry and orientation of the parts to be extracted.

We chose to still report capacity in TIE for better comparison with historical data. However, one should keep in mind that a given TIE capacity can lead to different volumes if the company serves non-wafer applications.

<table>
<thead>
<tr>
<th>Parts Geometry</th>
<th>2” c-plane core extraction</th>
<th>2” c-plane slabs</th>
<th>137 x 70 mm a-plane slabs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable mass</td>
<td>112</td>
<td>139 kg</td>
<td>140 kg</td>
</tr>
<tr>
<td>Material Yield</td>
<td>47.5%</td>
<td>59%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Boule dimensions: 500 mm diameter x 300 mm height / 235 kg
Material Capacity
Top 20 manufacturers.

Growth Capacity Q1-2014 (million mm of TIE per month)

- The top 3 remains unchanged and represent 26% of the total capacity.
- The top 20 represent 77%.
- There are now 9 Chinese companies in the top 20.
- Procystal capacity = XXXk in Taiwan + XXXk in new facility in China. However, some of the capacity in CN might stem from furnaces transferred from Taiwan.
- The GTAT capacity reported is for the Salem, NH facility. Although, we believe those furnaces are currently essentially used for process development. Capacity at the new Mesa, AZ is NOT included here.
Focus on China
Overview

- Since 2009, we’ve tracked a total of 93 companies active or planning to enter the sapphire market.
- We believe that at least 10 projects have already pulled the plug or stopped before construction started. Among the highest profile where GCL Opto, SKT and Kanglan which initially targeted a combined capacity of more than 2.5 million TIE per month.
- Most of the new entrants rely on growth technologies acquired abroad (GTAT, ARC Energy, Thermal Technology and multiple Eastern European Kyropoulos vendors). However there are now credible equipment manufacturers in China.
- There are more than 80 LED epitaxy companies in China. More than half of them are likely to disappear within the next 2-3 years. But strong leaders are emerging (Sanan, ETI, Epilight, Yangzhou Zhongke Semiconductor, Nationstar, Tsinghua Tongfang, HC Semitek, Silan Azure..)

Leading Companies:
- Crystaland, Aurora, Silian
- Emerging: Unionlight, HTOT, Saifei, Shangsheng, TDG Core, NJ-Crystal, Crystal Optech etc…
Supply vs. Demand: Scenario #2: Adding Display Cover

Display Cover Demand Scenario

- 2012: (chart data)
- 2013: (chart data)
- 2014: (chart data)
- 2015: (chart data)
- 2016: (chart data)
- 2017: (chart data)
- 2018: (chart data)
- 2019: (chart data)

Legend:
- Display covers - Others
- Display covers - Apple (non captive)
- Smartwatch
- CE
- LED
- Total

Note: excludes 80% of Apple need considered captive at the GTAT Mesa facility.
LED Filament Materials

- Various materials are used for the COB substrates: Glass, Ceramic, Sapphire.
- Glass and ceramic are still widely used due to low cost and broad availability compared to sapphire:
  - Glass filament substrates: from CNY 0.3/piece.
  - Ceramic filament substrates: from 0.4 CNY / piece
- **Sapphire is currently emerging as the preferred material** due to:
  - High mechanical strength, good thermal conductivity (compared to glass) and perfect thermal expansion coefficient match with the LED die.
  - ASP decreasing quickly as manufacturing technologies mature: from about 1.2 CNY a year ago to ~ 0.6 CNY (range: 0.48-0.8) currently.
- However, it remains to be seen which of sapphire or translucent alumina ceramics will win in the long term.

Glass-based filament
(source: UVTM)

Close up of an assembled filament
(www.superbrightleds.com)
Sapphire has been used in luxury watches since the 1930’s. Today’s, most “luxury watches” watches have sapphire windows obtained by the Verneuil method\(^1\).

However, the Verneuil method is limited in size (1-1.5“ diameter max) and “Smartwatches” have rather large displays. This provides opportunity for non alternative bulk growth technologies to capture this market despite their higher cost.

Some smartwatch models announced at the CES 2014 feature a sapphire display cover. However, the current market leader, Pebble announced it’s new flagship model will use Gorilla Glass.

Cost Structure Comparison
(US$/kg)

The Wellness Watch by Wellograph features a sapphire display cover (source: company)

\(^1\) This market is discussed in details in our “Touch Screens, Displays, Semiconductor, Defense & Consumer Applications of Sapphire” report
Cost Simulations
Display Cover Dimensions:

- At the time of publishing the first version of this analysis in November 2014, very little information was available regarding the size of the future iPhone 6 display. But recent studies indicated that the vast majority of $400+ Android phone market was now constituted of 5” or larger displays, so we assumed that to respond to consumer demand, Apple would increase the display size compared to its previous models. At the time we chose to simulate a display cover with dimensions similar to the one used in by Samsung for its Galaxy S4 featuring a 5” display.

- Since then, it has became increasingly likely that Apple will for the first time release 2 models with different display size: 4.7” and 5.5”.

- For this edition, we have therefore simulated 2 different display size and used the following dimensions:

<table>
<thead>
<tr>
<th>Item</th>
<th>X</th>
<th>Y</th>
<th>Diagonal</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4.7” display</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Display</td>
<td>2.3”</td>
<td>4.1”</td>
<td>4.7”</td>
<td>11.9 cm</td>
</tr>
<tr>
<td>Display Cover</td>
<td>2.53”</td>
<td>5.37”</td>
<td>5.94”</td>
<td>15.08 cm 13.59 inch²</td>
</tr>
<tr>
<td><strong>5.5” display</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Display</td>
<td>2.7”</td>
<td>4.8”</td>
<td>5.5”</td>
<td>13.97 cm</td>
</tr>
<tr>
<td>Display Cover</td>
<td>2.93”</td>
<td>6.06”</td>
<td>6.73”</td>
<td>17.11 cm 17.76 inch²</td>
</tr>
</tbody>
</table>
Yield Impact on Cost and Capacity: Crystal Growth – 4.7”

- Crystal growth yields have a significant impact on cost although there’s diminishing returns when sufficiently high. In the sapphire growth industry, XX% yield would already be considered very good and XX% excellent. Only a handful of world-class sapphire makers consistently reach such levels.
- We consider that yields the XX-XX% range were probably used as the base of discussion between Apple and GTAT to agree on initial price, and capacity. However, as of late July 2014, only one month after the Mesa plant started operated at full capacity, we believe that yields are much lower, probably in the XX-XX% range. The company must therefore rapidly improve this number in order to meet shipment volume targets\(^1\) and improve its cost position to achieve initial revenue and gross margin guidance.

\(^1\): per their initial agreement, if GTAT can’t meet its supply commitment, it will bear ALL cost associated with Apple having to source material from another vendor.
• **Capacity/Capability (Q1-2014)**
  – The company has developed an in-house Kyropoulos-type of growth technology called TSTGT (Top Seeded Temperature Gradient Technique) that features CZ-like seeding and diameter control procedures.
  – As of Q4 2013, the company grows 100 kg boule but is currently upgrading the technology to 150 kg by mid 2014 and is currently developing 300kg systems.

• **Sapphire Revenue (estimates):**
  – 2012: US $XX million
  – 2013: US $XX million

![Graph of Sapphire Ingot mm of TIE](image)

![Graph of Sapphire Wafer TIE K/month](image)

![Graph of Xinjing Sapphire capacity expansion plan](image)
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