Challenges in the Supply Chain for Advanced Materials

Mark Thirsk
mthirsk@linx-consulting.com
+1 617 273 8837
Linx Consulting Service Portfolio

- **Multi-Client Reports**
  - IC Materials
    - CMP
    - Deposition
    - Patterning
    - Cleaning
    - Gases
  - III-Vs, TSV, WLP, Solar

- **Proprietary Projects**
  - Market Planning
  - M & A
  - Growth and Diversification
  - Supply Chain Optimization
  - Technology Commercialization
  - Strategic Planning
  - Voice of the Customer

- **Econometric Semiconductor Forecast**
  - Financial planning
  - Sales and Operational planning
  - Forecasting

  *Hilltop Economics LLC*

- **Cost Modeling**
  - Client demand modeling
  - Product development
  - Bill of Materials quantification

  *IC Knowledge, LLC*

- **Semi**
- **Packaging**
- **Nano Technology**
- **LCD**
- **PV**
- **LED/ Compound Semi**

Semicon Techxpot 2016
The Development of Computing

1.00E+00 1.00E+03 1.00E+06 1.00E+09 1.00E+12 1.00E+15 1.00E+18 1.00E+21 1.00E+24


FLOPS

1000000000000000000

7 Bn Human Brains

2 Week Weather Forecast

Real Time Single Brain Simulation

Folding@home

Watson

GPUs

Core i7

Mobile GPU

Serialzed human thought

Mainframes / Distributed

Office based

Semicon Techxpot 2016

www.linx-consulting.com
Silicon Follows GDP Closely

93-15Q4
95% correlation
MSI Multiple: 2.1X

Source: Hilltop Economics
Semicon Techxpot 2016
www.linx-consulting.com
Real Investment Critical for Silicon Demand

Million Square Inches

- SEMI MSI
- Real Investment, 44 Consensus Countries

93-15Q3
96% correlation
MSI Multiple: 1.67X

Source: Hilltop Economics
Semicon Techxpot 2016
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Electronic System Growth Drivers

• Internet of Things
  – Much hyped driver of billions of networked devices generating information for governmental, commercial, consumer, medical, and other information systems

• Virtual Reality
  – Creation of virtual displays of real and simulated environments for military, consumer, commercial and other applications, usually through a novel head display

• Artificial Intelligence
  – Computer based intelligent learning systems

• Autonomous Vehicles
  – Sensor systems supporting vehicle based computer systems offering various degrees of driver assistance including fully autonomous driverless vehicles.
Data from sensors processed and transmitted. Actuators and systems to implement smart networks and systems.

Computers and smart mobile devices act as interfaces and hubs.

Billions of devices over the next 10 years.

Revenue derived from data services.

The majority of wafer demand will be in older technology, supported by web or cloud based data services.
Virtual Reality

Comparative Display Complexity

Mpxixels

0 40 80 120 160 200

Avg Gaming PC High End Gaming PC 4K Gaming PC Stereo VR

Comparative Refresh Rate

MHz

0 40 80 120 160 200

Avg Gaming PC High End Gaming PC 4K Gaming PC Stereo VR

Baseline ~ 2 Mpxixels
Artificial Intelligence

- AI Research to develop machine based learning and intelligence.

- Deep learning to speed search and machine based speech and image recognition.

- Significant processing power either in local or cloud based settings.

- AI systems will need significant local or web based processing power.
Autonomous Vehicle Control
# Growth Drivers

## Electronic System Growth Drivers

<table>
<thead>
<tr>
<th>Driver</th>
<th>Need</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IOT</strong></td>
<td>Cloud compute</td>
<td>Logic</td>
</tr>
<tr>
<td></td>
<td>Communications</td>
<td>Memory</td>
</tr>
<tr>
<td></td>
<td>Distributed Devices</td>
<td>Analog</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Modems</strong></td>
</tr>
<tr>
<td><strong>Virtual Reality</strong></td>
<td>Computational Power</td>
<td><strong>Logic / Graphics</strong></td>
</tr>
<tr>
<td></td>
<td>Graphics</td>
<td>Memory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Analog</td>
</tr>
<tr>
<td><strong>Artificial Intelligence</strong></td>
<td>Computational Power</td>
<td><strong>Logic</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Memory</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Analog</strong></td>
</tr>
<tr>
<td><strong>Autonomous Vehicles</strong></td>
<td>Computational Power</td>
<td><strong>Logic / Graphics</strong></td>
</tr>
<tr>
<td></td>
<td>Sensor devices</td>
<td><strong>Analog</strong></td>
</tr>
<tr>
<td></td>
<td>Distributed Devices</td>
<td><strong>Power</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sensors</strong></td>
</tr>
</tbody>
</table>

Semicon Techxpot 2016
Beyond Moore

Sources: ITRS 2011, Nikonov and Young, IEEE JxCDC, 1, 3-11 (2015); Manipatruni, Nikonov and Young, Arxiv cond-mat 1512.05428 (2015)
ITRS 2.0

Geometric Scaling, 1975 - 2003
Reduction of horizontal and vertical physical dimensions, combined with improved performance of planar transistors.

Equivalent Scaling, 2004 - 2020
Reduction of horizontal dimensions only, introduction of new materials, and new physical effects. Vertical structures replace the planar transistor.

3D Power Scaling, 2021 - ?
Transition to vertical device structures. Heterogeneous integration with reduced power consumption.

Source: Gargini – ITRS 2.0
Semicon Techxpot 2016
www.linx-consulting.com
ITRS 2.0

International Roadmap for Devices and Systems

Source: Gargini – ITRS 2.0

Semicon Techxpot 2016
MARKET DRIVERS FOR MATERIALS
Q4 2015 Silicon Capacity

Source: semi, Linx Consulting

Semicon Techxpot 2016
Silicon Demand – 2015
MSI

Total = 9,562.4
Linx Materials Index

$/sqin


Volume slowdown
ASP decline

Process complexity
Modest growth

Process simplification
Modest growth

Semicon Techxpot 2016

www.linx-consulting.com
Technology Driven Material Cost

Bill of Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost ($)</th>
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<tbody>
<tr>
<td>Discrete 200mm</td>
<td>0.02</td>
</tr>
<tr>
<td>Analog 200mm</td>
<td>0.27</td>
</tr>
<tr>
<td>Logic 200mm</td>
<td>1.15</td>
</tr>
<tr>
<td>16nm NAND 300mm</td>
<td>2.25</td>
</tr>
<tr>
<td>20nm Logic 300mm</td>
<td>2.94</td>
</tr>
<tr>
<td>20nm DRAM 300mm</td>
<td>3.23</td>
</tr>
</tbody>
</table>

Source: Linx, IC Knowledge

Semicon Techxpot 2016

www.linx-consulting.com
3D NAND BOM Forecast

Source: Linx, IC Knowledge
Logic BOM Forecast

$/sqin

- Wet etch chemicals
- Wet clean chemicals
- Spin-on
- Reticles
- PVD targets
- Plating chemicals
- Monitor wafers
- Lithography materials
- Implant sources
- Dry etch gases
- CVD precursors
- CMP consumables
- Bulk gases
- Anneal gases
- ALD
- Wet strip chemicals

Source: Linx, IC Knowledge

Semicon Techxpot 2016
Lithography Extension Options

<table>
<thead>
<tr>
<th></th>
<th>Resolution</th>
<th>Defectivity</th>
<th>Throughput</th>
<th>Overlay</th>
<th>LWR</th>
<th>Inspection</th>
<th>Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>DSA</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

- Patterning will combine the best technologies to solve cost and capability challenges.
- EUV struggling to achieve maturity for 7nm, but may be implemented in later designs.
- EUV targeted for 5nm logic cut and critical masks.
- Introduction will require multiple ancillary materials for patterning stacks.
- DSA still needs development of experience and ecosystem, but vias and contacts are preferred entry points.

After Sematech
EUV Photoresist Forecast

EUV demand scenarios

- Device driven by analysis of lithography pitches and layer counts derived from real-world device analysis.
  - This demand scenario exists without constraints of equipment capability, or supply chain limitations.

- Tool shipment demand scenario can be driven off EUV exposure tool availability, and tool capability.
FEOL

- STI Extension
  - Vacuum based deposition
  - Improved spin-on material
  - Ge epitaxial deposition

- RMG
  - Novel work function and barrier precursors
  - Novel spacer (oxide and nitride) precursors
  - Improved contact resistance

- Cleans
  - Selective processes
  - Improved PRE with lower damage
  - Atomic layer processes

- Patterning
  - Multiple new materials for EUV
New lkd Precursors
Si containing porogens

Air Gap

New barrier stacks
ALD Ta & TaN
TiN
CuMn
MnN
Ru

New liner materials
Co
Ru
NiSi

Selective cap deposition

Improved sealing layers

Improved ECD additives

CVD flowfill Cu

CVD Cobalt fill

Silyl based lkd repair materials

Subtractive etch of Copper

Spin-on lkd materials
3D Crosspoint Array

3D XPoint™ Technology:
An Innovative, High-Density Design

- Cross Point Structure
- Stackable
- Non-Volatile
- High Endurance
- Transforming the Memory Hierarchy
- ~8x to 10x Greater Density than DRAM

PCM (Phase Change Memory)
OTS (Ovonic Threshold Switch)
New Material Dep, Etch, Clean, Passivation

Source: Ping - AMAT

(Intel 2009 publication)
Novel Challenges in Packaging

- Fan Out Hybrid WLP being aggressively pursued.
- Panel molding resins needed:
  - Low T cure
  - Matched CTE
  - Stable for reflow
- Photosensitive Dielectrics
  - Aqueous develop
  - Low CTE
  - Low cure Temp
  - Cheap
- Move to high resolution RDL, with interposerless designs, with die-first and die-last options.
  - Close to waferfab BEOL processes

Source: Fraunhofer Inst.
# Worldwide Wafer Fab Materials Forecast

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ALD</td>
<td>$274</td>
<td>$359</td>
<td>$472</td>
<td>$895</td>
<td>27%</td>
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<tr>
<td>CVD</td>
<td>$1,049</td>
<td>$1,289</td>
<td>$1,499</td>
<td>$1,947</td>
<td>13%</td>
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<tr>
<td>PVD</td>
<td>$677</td>
<td>$704</td>
<td>$792</td>
<td>$830</td>
<td>4%</td>
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<tr>
<td>Plating</td>
<td>$174</td>
<td>$192</td>
<td>$227</td>
<td>$305</td>
<td>12%</td>
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<tr>
<td>Spin On Dielectrics</td>
<td>$443</td>
<td>$572</td>
<td>$695</td>
<td>$712</td>
<td>10%</td>
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<tr>
<td>Pads and Slurries</td>
<td>$1,825</td>
<td>$1,930</td>
<td>$2,093</td>
<td>$2,191</td>
<td>4%</td>
</tr>
<tr>
<td>Wet Chemicals</td>
<td>$2,275</td>
<td>$2,358</td>
<td>$2,491</td>
<td>$2,584</td>
<td>3%</td>
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<tr>
<td>Lithography Materials</td>
<td>$2,701</td>
<td>$2,947</td>
<td>$3,505</td>
<td>$4,150</td>
<td>9%</td>
</tr>
<tr>
<td>Etchant Gases</td>
<td>$217</td>
<td>$232</td>
<td>$249</td>
<td>$306</td>
<td>7%</td>
</tr>
<tr>
<td>Dopant Gases</td>
<td>$234</td>
<td>$243</td>
<td>$253</td>
<td>$285</td>
<td>4%</td>
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<tr>
<td>Litho Gases</td>
<td>$128</td>
<td>$158</td>
<td>$194</td>
<td>$320</td>
<td>20%</td>
</tr>
<tr>
<td>Bulk Gases</td>
<td>$1,344</td>
<td>$1,419</td>
<td>$1,500</td>
<td>$1,751</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Total (Direct Mats)</strong></td>
<td>$11,343</td>
<td>$12,404</td>
<td>$13,971</td>
<td>$16,274</td>
<td>7%</td>
</tr>
</tbody>
</table>
Chemical Quality and Defectivity for 10m

Direct control of raw material quality
• Close sub supplier collaboration and integrated quality systems
• Vertical integration where possible

Holistic approach to particle control
• State-of-the-art filtration optimized for each chemical
• Optimized in-line, on wafer, and off-line particle and defectivity monitoring

Advanced statistical process control
• Feed forward and feedback SPC
• Sophisticated analytical tools

Design for cost and environmental impact
• Aqueous and environmentally friendly formulations are preferred
• Limit the use of custom constituents and additives
Supplier Landscape

China
• Continued acquisition and activity from multiple companies.
• Leveraged government equity positions to enable significant size acquisitions.

Acquisition Landscape
• Tsinghua Unigroup (China): Spreadtrum, RDA, WD, Powetech…..
• Lam Research – KLA/Tencor
• Beijing E-Town Investment (China) – Mattson Technology Materials
• KMG - OMG + General Chemical
• Entegris - ATMI
• Merck - AZ
• Merck – Sigma Aldrich & Solmet
• Wonik – Nova-Kem
• NATA (China) - Kempur
• Air Liquide – Air Gas
• Air Products – Versum Spinout
• SK - OCIM
• Dow Chemical – Dow Corning
• Dow Chemical - Dupont
Material Scaling Trends

• Equivalent Scaling
  – Cost of litho exploding
  – CMP enabling processes and surfaces
  – Implant enabling surface modification
    • Carbon implant
    • Silicon Implant
    • LER modification

• 3D Scaling
  – CVD and Etch will be the key processes
    • Aspect ratio
    • Vertical wall angles
    • Conformal coverage
  – Litho reliance relaxed, but interconnect density challenging
  – Collapse control driving use of surface modification and supercritical rinses and drying

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Conclusions

- Drivers for industry growth are changing, but there will continued demand for current device types.

- Roadmap trends will drive to 3D device architectures in the medium to long term. System specific hybrid packages, device types, and device architectures will extend the roadmap.

- New device architectures will shift requirements of critical materials for different devices.
  - Lithography extension is a primary cost driver.
  - 3D devices will challenge aspect ratios, placing focus on etch and deposition capabilities.

- The shift from planar scaling to 3D will extend into the packaging realm as some functionality and interconnect is moved into the wafer level package.

- Quality and defectivity requirements continue to be incredibly challenging, and require supply chain engagement.