Critical Challenges in Materials Supply to Advanced Semiconductor Manufacturing Fabs

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Key factors in gas supply.

New materials, processes, and adaptable supply chain to meet evolving market needs

- **Scale**
  - Larger fabs and smaller devices mean more gases

- **Quality**
  - Changing needs due to complex technology

- **Supply chain**
  - Complex global supply chain management

- **Sustainability**
  - Reduce environmental impact
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Scale. Drivers for increased consumption.

Rapid deployment of very large fabs

- Typical logic foundry now 80,000 WSPM
- Typical memory fab now exceeding 120,000 WSPM
- Fabs concentrated in clusters (science parks)
Scale. Several hundred process steps and hundreds of gases and chemicals.
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**Scale. Drivers for increased consumption.**

### Multi-patterning

- Move from single-patterning to multi-patterning because of small devices
- Small feature size requiring better optical resolution and move to EUV lithography
- Increased transistor processing (epitaxy, etch, ALD) driving new and increased materials

![Number of layers by node](chart.png)

**Graph source:** Credit Suisse
Scale. Drivers for increased consumption.

Move to more complex 3D devices

- 3D FinFET
  - Increased epitaxy steps
  - Increased ALD

- 3D NAND
  - Complex etch
  - Increased deposition
Scale. Increased use of nitrogen.

- Increasing fab capacity drives more consumption
- Advanced technology nodes use more $N_2$ due to more tools driven by multi-patterning
- Need for on-site generators with increased capacity as gas need increases

**Process node (nm)**

**Typical fab size (WSPM)**

**$N_2$ consumption (Nm$^3$/h)**
Scale. Increased use of hydrogen.

Compressed gaseous hydrogen (CGH₂)
- Economical transport for short to medium distances

Liquid hydrogen (LH₂)
- Economical transport for medium to long distances
  (only in U.S. and Europe)

On-site production
- Production through steam reforming or electrolysis
- No hydrogen transport costs
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Quality. **Drivers.**

- Complexity of processes and reduced yield with each added process
- Risk from higher investments and operational costs
- Engineers not knowing how a specific impurity might impact performance: the challenge of the unknown

**Semi manufacturing yields and steps**

![Graph source: Entegris](image)

<table>
<thead>
<tr>
<th>Technology node in nanometers</th>
<th>Relative yield</th>
<th>Process steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
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<tr>
<td>65</td>
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<td>45</td>
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<td>32</td>
<td>32</td>
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<td>28</td>
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<td>14</td>
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<tr>
<td>10</td>
<td>10</td>
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</tbody>
</table>
Quality. Increasingly important for chip manufacturers at leading technology nodes.

- A modern high-volume semiconductor fab hugely amplifies value and cannot afford any process excursions
- Stringent focus on controlling variation in all inputs to the chip fabrication process

**Starting wafer**
- Typical cost = $120
- Fab CAPEX now >$7B
- 40K to 80K wafer starts per month

**Fabrication**
- Advanced logic:
  - # process steps > 600
  - Cycle time 6 to 10 weeks
  - Processing cost = ~$1,000 - $5,000

**Finished wafer**
- Cost per processed wafer = $1,000 - $5,000
- “Value” up to $20K - $40K (based on ASP of the chips)

**IC chip**
- Average selling price ~$1 to > $2000
Quality. Need for holistic system.

Challenges in meeting demands

- Increase in complexity of monitoring and ensuring process stability across the entire supply chain
- An increasing demand for people such as materials scientists, chemists, and process engineers
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Quality. Need for holistic system.

- Measurement systems
- Gas distribution systems

- Receiving
- Prep
- Purification
- Fill
- QA/QC/Lab
- Delivery

Final product quality

Traditional quality focus

Measurement systems analysis (MSA), Statistical process/Quality control (SPC/SQC)
Quality. Reduce variability, tighten control limits.

IC technology step changes drive electronic materials purity and analytical requirements

<table>
<thead>
<tr>
<th>15 to 20 years ago</th>
<th>Within the last 10 years</th>
<th>Recent / Present</th>
<th>Near future</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-purity EMs</td>
<td>High-purity EMs</td>
<td>High-purity EMs</td>
<td>High-purity EMs</td>
</tr>
<tr>
<td>Tight consistency</td>
<td>Tighter consistency</td>
<td>Use of overall process control system</td>
<td>Use of overall process control system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fingerprinting</td>
<td>Fingerprinting</td>
</tr>
</tbody>
</table>
Quality. Reduce variability, tighten control limits.

A need for process stability across the entire supply chain

- Rigorous measurement, enabled with fingerprinting and metrology
- Gas purity and consistency/reliability
- Business continuity planning
- Process/statistical quality control
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Supply chain. Global supply chain comes with challenges.

- Capacity planning
  - Usage volumes for specialty gases
  - Visibility into ramp demand of materials for new technologies
- Limited raw materials suppliers
- Security of supply and move to local and regional suppliers
- Natural disasters and shortages
- Transportation labor strikes
- Change in government regulations

Japan earthquake and tsunami devastation – Source: LA Times
Supply chain. Interlinked, comprehensive, customer-focused.

- Chinese government block of hazardous materials into multiple ports during the 2008 Olympics
- Materials had to be trucked in and added two months extra delivery time
- Required a lot of advanced planning

- Conduct Business Continuity Planning (BCP) with alert nodes in proactive processes
- Identify potential supply gaps by plotting product-source mapping
- Create raw materials, manufacturing, transportation, and labor shortage contingency plans
- Develop supply gap mitigation and implementation plans

- Assess where and how to invest to diversify supply chain on multiple continents
- Do procurement forecasting and planning with customers and suppliers to meet demands
- Acquire two sources for raw materials and have customers qualify both sources
- Establish footprint closer to customer with on-site and local supply plants
- Coach suppliers on Statistical Quality Control (SQC), Statistical Process Control (SPC), and customer requirements to show things they do can help customers avert disaster at multiple points in the supply chain
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Sustainability
Reduce environmental impact
**Sustainability. Big fabs, big use of resources.**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Usage Details</th>
<th>Equivalent (enough for)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td>10 cubic meters used per wafer at 14 nm node x 80,000 wafers per month x 12 months = 9,600,000 cubic meters of water used per year</td>
<td>39,506 people in U.S.</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td>1220 kilowatt per hour used per wafer at 14 nm node x 80,000 wafers per month x 12 months = 1,152,000,000 kilowatt – hours or 1,152,000 megawatt – hours electricity used per year</td>
<td>94,846 people in U.S.</td>
</tr>
<tr>
<td><strong>Natural gas</strong></td>
<td>61 cubic meters used per wafer at 14 nm node x 80,000 wafers per month x 12 months = 58,560,000 cubic meters of natural gas used per year</td>
<td>26,899 people in U.S.</td>
</tr>
<tr>
<td><strong>Greenhouse gases</strong></td>
<td>8 greenhouse gases used, which if unabated, are the equivalent of 4.2 tons of CO₂ per wafer. After 90% abatement at 14 nm node x 80,000 wafers per month x 12 months = 400,000 tons CO₂ equivalents used per year</td>
<td></td>
</tr>
</tbody>
</table>
Sustainability. Big fabs, big carbon footprint.

Annual carbon footprint including electricity, natural gas, and chemicals of just one 80,000 wafers per month capacity fab = 1,300,000 tons CO$_2$.
Sustainability. Drivers.

- Increasing environmental focus and concerns
- Heightened environmental regulations
- Use of large volumes of rare and high value gases
- Pressure to reduce operating costs

SPECTRA® nitrogen plant (world’s best energy efficiency)
Sustainability. Material recovery solutions.

On-site, closed-loop recovery
- Materials recovered on site, purified, and are available for re-use in the manufacturing process

On-site, open-loop recovery
- Materials recovered on site and are available for use in other applications

Off-site recovery
- High-cost materials recovered, shipped off site, and purified at an external facility for re-use

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>Recovered on-site and returned to customer</td>
</tr>
<tr>
<td>Argon</td>
<td>Recovered on-site and returned to customer</td>
</tr>
<tr>
<td>Xenon</td>
<td>Recovered and processed off-site</td>
</tr>
<tr>
<td>Sulfur hexafluoride</td>
<td>Recovered on-site and returned to customer</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>Recovered on-site and sold to industrial users</td>
</tr>
</tbody>
</table>
Sustainability. Fluorine.

Fluorine technology to reduce emissions by tens of million tons of CO₂ equivalent per year

Global warming potential of greenhouse gases
(100 year GWP kg CO₂ eq)

<table>
<thead>
<tr>
<th>F₂</th>
<th>NF₃</th>
<th>SF₆</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>17,200</td>
<td>22,800</td>
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Sustainability. Fluorine.

Fluorine technology to reduce emissions by tens of million tons of CO$_2$ equivalent per year

Case example: Major memory fab

- Using on-site fluorine plants as a safer and more cost-effective alternative to cylinder fluorine for cleaning Chemical Vapor Deposition (CVD) chambers in its manufacturing process

- Using fluorine to replace other fluorinated cleaning gases such as nitrogen trifluoride (NF$_3$) following tests that demonstrated reductions in cleaning time of up to 40% and a 35% decrease in the mass of gas used
Implications for manufacturers.

Proactively plan up front

Partner with suppliers who
- Commit to your needs
- Value and implement process control and measurement
- Provide security and diversity of supply

Do longer term planning to include
- Building of on-site gas production and recovery
- CAPEX investments