Reducing $/Wp of Thin Film Si Through Materials Cost, Scale and Technology

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Linde Electronics
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Introduction to Linde

Drivers for Cost Reduction

On-Site Production of Key Gases

Cost Reduction Roadmap
Linde is a $19B global gas and engineering company with business in over 100 countries worldwide and global solar customer base.
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Cost Reduction Roadmap
Typical Gas Cost Breakdown for Thin Film Silicon

**OEM A**
- **Silane**: 40%
- **NF3/F2**: 39%
- **Dopants**: 7%
- **N2**: 3%
- **H2**: 10%
- **Others**: 1%

**OEM B**
- **Silane**: 44%
- **DEZ**: 26%
- **Dopants**: 8%
- **N2**: 2%
- **H2**: 1%
- **Others**: 17%

**OEM C**
- **Silane**: 44%
- **NF3/F2**: 36%
- **Dopants**: 5%
- **N2**: 7%
- **H2**: 8%

Silane, Cleaning Gas and Bulk H2/N2 are key cost components
Factors Influencing Cost of Materials in the Process

Direct Material Cost
- Recipe and Consumption Rate
- Delivery Scheme
- Market Conditions
- Materials Choice

Scale of Manufacturing
- On Site Generation
- Volume Cost Benefits
- Site and Location Benefits

Technology
- Throughput Improvement
- Efficiency Improvement
- Yield Improvement

Linear Benefit
- Disproportional Benefits
Gases have significant impact over and above material cost.
Leveraging gas technology is critical for cost reduction.
Linde Solar Technology Development Programmes
All development activity focused on reducing $/Wp

Source: BA Electronics analysis
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On-Site Production of Key Gases

Cost Reduction Roadmap
Is onsite production the right choice for gases?

Benefits

• Secure supply. No dependence on multiple weekly or daily trailer deliveries

• Lower cost. Reduced transportation costs. No liquid production cost (for H₂ and N₂). Improved COO (F₂)

• Increased safety: No frequent change-outs of toxic and flammable gas cylinders

• Reduced Carbon Footprint

Considerations

• Requires higher initial capital cost outlay for gas supplier

• Requires long term contract and minimum consumption by customer

• Requires back up schemes with on-site storage

On-Site Gas Production can reduce cost/Wp for high volume production
### Minimum production scale for viable on-site gas supply

**Tandem Junction Silicon Process**

<table>
<thead>
<tr>
<th>Annual Production in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
</tr>
</tbody>
</table>

#### Silane
- ISO Containers
- Over the fence supply

#### Clean Gas
- Scalable On-Site Fluorine Generator.

#### Nitrogen
- Small Packaged N2 Plants
- Large Scale N2 plants

#### Hydrogen
- Liquid or Gas H2
- Small Packaged H2 Plant
- Large SMR

<table>
<thead>
<tr>
<th>MW Produced/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Silane (MT/yr)</th>
<th>18-60</th>
<th>50-150</th>
<th>90-300</th>
<th>150-500</th>
<th>300-1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Gas (MT/yr)</td>
<td>65-70</td>
<td>160-175</td>
<td>325-350</td>
<td>550-575</td>
<td>100-120</td>
</tr>
<tr>
<td>N2 (Nm3/hr)</td>
<td>700-900</td>
<td>1800-2500</td>
<td>3500-4500</td>
<td>6000-7500</td>
<td>12000-15000</td>
</tr>
<tr>
<td>H2 (Nm3/hr)</td>
<td>30-250</td>
<td>75-700</td>
<td>150-1500</td>
<td>250-2500</td>
<td>500-5000</td>
</tr>
</tbody>
</table>

**Consumption rate depends on process and technology**

12/8/2009
Silane: Current Supply Scheme

Large Scale Polysilicon Plant  
>1000TPA Silane

— Most Silane is produced by major polysilicon manufacturers
— Major Industrial Gas companies purchase, repackage and deliver to end user
— Price and availability of Silane is highly variable

Stable Supply and Cost Reduction requires alternative supply model
Distributed Silane Production and Delivery

- Large Solar Cell Customer (>250MW)
  - Over the fence plus distribution
  - Some risk is shared
  - Gasco owns and operates Silane plant
  - Customer can co-invest in Silane production

- Small Solar Cell Customer (Over the fence)
  - Reduced cost of Silane
  - Guaranteed supply
  - Stable price
  - Reduced risk during container changes
  - Reduced Carbon Footprint

Direct Pipeline
- Some risk is shared
- Gasco owns and operates Silane plant
- Customer can co-invest in Silane production
- Reduced cost of Silane
- Guaranteed supply
- Stable price
- Reduced risk during container changes
- Reduced Carbon Footprint
Replacing NF₃ with On-site F₂ to address key throughput, cost & environmental concerns

**How?**

- **Higher Line productivity**
  - Reduce cleaning time by **50%**

- **Lower cost per clean**
  - 80 kg of F₂ delivers the same cleaning efficiency as 100 kg of NF₃

- **Lower environmental impact**
  - F₂ has **zero** global warming potential vs. 17,000 for NF₃

**Benefit**

- Increase line throughput by **up to 10%**
  - Direct material cost saving → 10-20% less mass of gas usage per clean
  - 60% reduced electricity consumption in plasma source

- Not subjected to current or future emission restrictions
  - Easier to abate

Modular On Site F₂ Solution:
Eliminates logistics of trailer supply chain and guarantees security of supply

12/8/2009
**Generation-\(F^\circ\)® - a modular solution for any thin film silicon line**

<table>
<thead>
<tr>
<th>MW CAPACITY</th>
<th>65 – 1 x TJ line</th>
<th>330 – 5 x TJ lines</th>
<th>1000 – 3 x Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonnes / yr F(_2)</td>
<td>~70</td>
<td>~350</td>
<td>~1150</td>
</tr>
<tr>
<td>Potential Saving over NF3 ($/year)</td>
<td>~$2.5M</td>
<td>~$11.7M</td>
<td>~$32.7M</td>
</tr>
</tbody>
</table>
Nitrogen: Variable size on-site generators for all size solar fabs

Threshold for N²-Onsite depends on proximity of fab to an ASU

Liquid assist plants use delivered liquid N₂. Compressor plants can operate without Liquid N₂

Typical lead time of small plants is 12-18 months

Initial production ramp is managed by Liquid N₂ tanks

Back up is by Liquid N₂ tanks

Pipeline possible based on location

Packaged Liquid-assist plants
250-2500 Nm³/hr

Packaged Compressor plants
350-3500 Nm³/hr

Large scale ASU
4200-15000 Nm³/hr
Onsite Hydrogen: Selection Considerations

- Is it possible to get Liquid H₂ delivery? For example in EU and US, LH2 is readily available but not so in Asia.

- Proximity to H₂ plant

- Natural Gas availability and quality

- Ramp schedule and full production demand

- Back up schemes with liquid or compressed H₂

Basics of On-Site H₂ Generation

- Smaller scale H₂ in remote regions can be produced by water electrolysis (< 50 Nm³/hr)

- On larger scale, H₂ is generated from Natural Gas (CH₄)
  \[ \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 3\text{H}_2 \]

- Quality of H₂ and purification requirements depends on quality of Natural Gas

- Other possible fuel sources include methanol and higher hydrocarbons
Hydrogen – large consumption drives on-site generation

Single Junction

• < 80 Nm³/hr
• Tube trailer/Liquid H₂/Electrolyser
• 3-6 months Leadtime

Tandem Junction < 300 MW

• 80-1000 Nm³/hr
• Small Packaged SMR
• Tube trailer back-up
• ~12 months leadtime

Tandem Junction > 300 MW

• 1000-4,200 Nm³/hr
• Large SMR
• 18-24 months leadtime

Hydrogen pipeline supply may be possible depending on location.
Natural Gas feedstock supply is critical to low cost production via SMR
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Cost Reduction Roadmap
Gases Value Improvement per Wp - 2011 Roadmap.

Note: Excludes cost of site distribution installation
Estimate additional US$0.02/Wp
Gases Value Improvement per Wp - 2013 Roadmap.

Note: Excludes cost of site distribution installation
Estimate additional US$0.02/Wp
Take-Away Messages

Gases have a disproportionate influence (more than just material cost) on total cost of production of thin film silicon solar cells

Gas technologies affect throughput, efficiency and yield

On-site plants for critical gases are necessary to meet logistical and cost challenges.

On-site production threshold depends on several factors
   — Technology of choice and gas consumption rates
   — Planned scale of operation
   — Proximity to Bulk Gas Manufacturing locations

Work closely with gas supplier through the planning process to determine needs
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