Sustainable silicon production

Erik Stensrud Marstein
Centre Director

The Norwegian Research Centre for Solar Cell Technology

The Norwegian Research Centre for Solar Cell Technology is located in various locations across Norway, including Trondheim, Oslo/Kjeller/Askim, Kristiansand, Årdal, Glomfjord, and Drag. The centre is supported by several research institutions and companies, such as NTNU (Norwegian University of Science and Technology), SINTEF, SEMILAB, IFE (Institute for Energy Technology), REC, Elkem, NoSun, and Norwegian Crystals. The centre focuses on the development and research of solar cell technology.
Agenda

- The solar revolution
- Silicon production for solar cells
- Sustainable silicon production
Solar powering the World

Data: IEA-PVPS (2016)
Solar powering the World

Data: IEA-PVPS (2016)
What do the numbers mean?

50 000 MW$_p$/y $\sim$ 300 – 500 km$^2$/y

10 – 15 billion solar cells/y

Silicon consumption: 250 000 (-ish) tons ($\sim$5g/W$_p$)

50 000 MW$_p$/y $\sim$ 75 TWh/y $\sim>$1.7 entire Denmark/y
Solar powering the World

The Swanson effect
Price of crystalline silicon photovoltaic cells, $/watt

Cumulative PV module shipments (MWp)
Average module sales price (USD 2011/Wp)

2013 price $0.74/watt

Source: Bloomberg, New Energy Finance

Bloomberg NEF, ITRPV
A silicon-based industry!

NPD Solarbuzz forecast for 2014
Silicon

- Group IV A element
- Abundant
- Industrially important
- Non-toxic
- Si never occurs pure in nature
  - Forms oxides and silicates
  - Challenge: making pure Si

### Physical properties of $^{14}$Si

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic weight</td>
<td>28.085</td>
</tr>
<tr>
<td>Atomic density</td>
<td>$5.0 \cdot 10^{22} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>Melting point</td>
<td>1410 °C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>2355 °C</td>
</tr>
<tr>
<td>Density</td>
<td>2.33 g cm$^{-3}$</td>
</tr>
<tr>
<td>Volume of contraction (on melting)</td>
<td>9.5 %</td>
</tr>
<tr>
<td>Energy gap</td>
<td>1.12 eV</td>
</tr>
<tr>
<td>Crystal structure</td>
<td>diamond</td>
</tr>
</tbody>
</table>
Silicon for solar cells

- Quartz
- MG Si
- Silanes
- Poly Si UMG
  - Cz Si
  - mc Si

Metallurgical route
Silicon for solar cells

- Quartz
- MG Si
- Silanes
- Poly Si UMG
- Metallurgical route
- Cz Si
- mc Si
Overall requirements

- Very high purity
  - Key requirement for high efficiency

- Low energy consumption

- High yield
  - «Chemical yield»
  - Process

- High throughput
  - Reduced CAPEX per kg$_{Si}$

LOW COST ($/kg_{Si}$)!
Material quality matters

- Module: 49%
- Cell: 22%
- Wafer: 13%
- Silicon (poly): 16%
- System: 22%

ITRPV (2013)
Material quality matters

SI WAFER QUALITY

«BAD Si»
«HIGH PERFORMANCE Si»

τ_{bulk} (s)

Cell efficiency (%)

J_{0,front} + J_{0,rear} (fA/cm^2)

«HIGH EFFICIENCY»
«LOW EFFICIENCY»

Haug & Marstein (2014)
Silicon production technologies

- Chemical silicon production
  - Silane-based production technologies

- Metallurgical silicon production
  - Metallurgical purification steps
Monosilane-based production of silicon

• …at least the overall reaction is simple…

SiH$_4$(g) $\rightarrow$ Si(s) + 2 H$_2$(g)
Monosilane-based production of silicon

• ...but the process is FAR more complex!
  • Reaction networks, nucleation, agglomeration, surface growth...

Silane-based production methods

Industry standard: Siemens + SiHCl₃

- Heated silicon rods
- Cooled outer wall
- Gas inlet and outlet
Monosilane-based production methods

Fluidized bed reactor

Siemens (SiH₄)

Free space reactor

Centrifugal CVD reactor

Heated silicon rods

Cooled outer wall

Gas inlet and outlet

Gas inlet

Exhaust

Heating elements

Particle nucleation

Exhaust and fines

Fluidization gas and reactant gas inlet

Gas inlet and outlet

Exhaust
The silicon production laboratory at IFE

- Control room
- Fluidized bed
- Freespace

Testing CCVD pilot - Dynatec
Silicon production processes: FBR

- Already in full production by REC Silicon
  - Lowest demonstrated energy consumption per kg$_{Si}$ in full production!
- Full scale production facility in Moses Lake (US)
- Major expansion underway
  - Yulin
Silicon production processes: C-CVDR

- Pilot scale production unit developed by Dynatec
  - Lowest demonstrated energy consumption per kg$_{\text{Si}}$
    - (< 5 kWh/kg$_{\text{Si}}$)
  - Extremely high production rates
    - (>100 µm/min)
  - High yield demonstrated
    - (~95%)
Silicon production processes – Elkem Solar

- Unique production technology
- Lowest emissions per kg$_{Si}$ in the World demonstrated
  - Low energy consumption
  - Norwegian energy mix
- New factory at Herøya opened this year
High performance silicon ingots & wafers

- Production of high performance Cz Si ingots and wafers
  - High efficiency requires extremely efficient wafers
  - Norsun supplies wafers to the most demanding customers in the industry
Conclusions

- The solar industry is growing
- Silicon is the material of choice in the industry
- Silicon is a Norwegian industrial strength
- Many opportunities for growth of the domestic industry
Thank you for the attention!