Solar grade silicon
Float Process for Silicon Wafers
Dye Sensitized Solar cells
Solar and wind on the electric grid
Supply Chain for Silicon Solar Cells

PV System = Solar cell module + Balance of system (BOS)

50% of system cost

30% of module cost

Crystalline silicon + Wafer production + Cell fabrication

Solar-grade silicon

Missing link

Insufficient

REC Silicon, Moses Lake, WA
Fluidized Bed Si Production:
2002–2005  Pilot plant
2005–2007  Demonstration scale
2008       Commercial scale

Limits 2006 industry growth to 5%??

$3-5/kg

Metallurgical grade silicon

SiCl₃H distillation

Decomposition

Crystallization

Wafer

Integrated circuit

$20-30/kg

$40-60/kg

Aim: $15/kg

Limits 2006 industry growth to 5%??

Aim: $15/kg

IC supply chain

$3-5/kg

$20-30/kg

$40-60/kg
Solar Grade Silicon using FBR

Current Methods:
- mgSi to TCS and pyrolysis in “bell” reactors (Siemens Dow-Corning, Wacker, +)
- mgSi to TCS to Silane and pyrolysis in bell reactors (Union Carbide - REC Silicon)
- Silane from SiO2 and silane pyrolysis in fluid bed (Ethyl Corp – MEMC)
- Direct reduction and purification (metallurgical route, Elkem, Dow-Corning)
- Fluid bed silane pyrolysis (REC Silicon, MEMC)
- +++

**Siemens Reactor**
Batch Process
1100°C (TCS)
650 °C (Silane)

**Fluid Bed Reactor**
Continuous Process
Large surface area
650°C

$SiH_4(g) \rightarrow Si(s) + 2H_2(g)$

increase throughput
Reduce energy cost
Integrate over time for particle size distribution

Multi-scale model for Scale-up and Design

Integrate over height for granular yield

Simulation to obtain model input

Operation challenges

Fast dynamics – fluidization, reaction
Slow dynamics – particle size distribution
Distributed parameters
- Particle size distribution
- Chemical reaction, yield loss
- Bed fluidization

Commercial Process Built in 2009
Silicon Wafers using Float Process

Current methods are carried out in batch
Continuous processes yield inferior product

Single crystalline  18-20%
Multi-crystalline  14-16%

Edge-Defined Film Fed Growth (EFG)
The Pilkington float Glass Process

Replaced the drawn glass process in 1960ies
High throughput
Low cost (capital and operating)
Very high quality glass
In line processing is possible (CVD)
Float Process for Silicon Wafers

2009-2013 NSF grants* to study
- crystallization
- fluid flow and heat flow
- process scale-up and detailed design
- process control
- commercialization

* Grant to CMU for fundamental studies and NSF SBIR for iLS for commercialization
Simulations show that the Silicon melt has to be floated on the substrate and the temperature should be maintained such that there is a liquid layer between the solidified Silicon and the substrate.

The criteria is satisfied experimentally, and as a result, Silicon is retained in the form of sheet (Top).

Cross-sectional SEM-micrograph showing ~300-400 µm thin sheet of Silicon produced on the substrate after solidification (Bottom).

Silicon sheet with substrate at the boundaries – easy removal of wafers from the medium.

XRD result of Si sheet cast over the molten substrate. As-grown Silicon sheet shows the peaks of SiO_2 cristobalite (\(\nabla\)), Lead (\(\bigcirc\)) and Tin (\(\bullet\)).

The inset shows the enlargement without the complete, highly textured, probably single crystals, Si<111> peak.

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Mullins-Sekerka Instability – Spherical Instability

\[
\frac{d\delta_i}{dt} = \frac{D(l-1)}{(C-c_R)R} \left[ \frac{G}{R^2} \frac{c_0 \Gamma_D}{(l+1)(l+2)} \right] \delta_i
\]

Concentration gradient favors growth of harmonic

Capillary effect favors decay of harmonic
Stability of Float Process for Silicon Wafers

Theory: Stability and process modeling

Experiments: Water models
Dye Sensitized Solar Cells (DSC)

- First shown in labs circa 1991 by Gratzel et al.
- 3rd generation solar cell, utilizing a thin film of TiO$_2$ nanoparticles
- TiO$_2$ particles, coated with a dye, act as the photoanode
- Materials are inexpensive, but only low efficiencies are possible without costly processing

Intention – to use surface science and electrochemistry to create an ordered layer
- reduce distance through which electrons must migrate
- Layer should be sufficiently conductive without sintering at 450° C, enabling the use of plastic substrates
Evanescent wave scattering allows us to observe the presence, approach, and departure of particles from a surface, enabling deeper insights into the kinetic process of electrophoretic deposition. This is valuable not only for DSC, but for all thin-film processes utilizing electrophoretic deposition of micro to nano scale particles.

\[ I(h) = I_0 \exp \left( -\beta h \right) \]

\[ \beta = \frac{4 \pi}{\lambda} \sqrt{(n_1 \sin \theta_1)^2 - n_2^2} \]