Solar Cell Research

CAPD Review Sunday March 7, 2010

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Solar grade silicon

Float Process for Silicon Wafers

Dye Sensitized Solar cells

Solar and wind on the electric grid

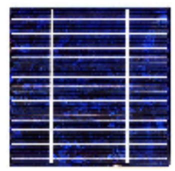
Supply Chain for Silicon Solar Cells

50% of system cost

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

30% of module cost

Crystalline silicon → Wafer production → Cell fabrication



REC Silicon, Moses Lake, WA

Fluidized Bed Si Production:

2002–2005	Pilot plant
2005–2007	Demonstration scale
2008	Commercial scale

Solar-grade silicon

Missing link

Insufficient

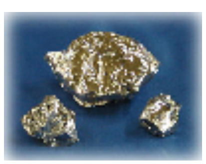
Limits 2006 industry growth to 5%??

Aim: $15/kg

$20-30/kg

IC supply chain

Metallurgical grade silicon → $SiCl_3H$ distillation → Decomposition Crystallization → Wafer → Integrated circuit



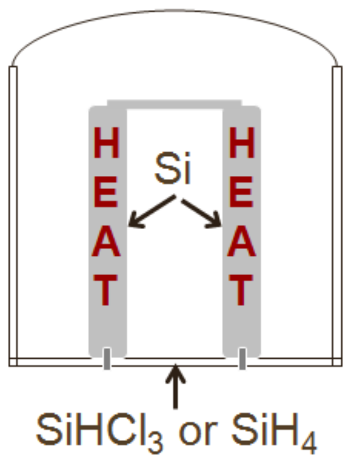
$3-5/kg

$40-60/kg

Solar Grade Silicon using FBR

Current Methods:

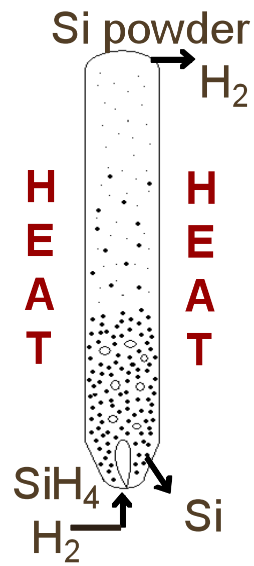
- mgSi to TCS and pyrolysis in “bell” reactors (Siemens Dow-Corning,Wacker,+)
- mgSi to TCS to Silane and pyrolysis in bell reactors (Union Carbide - REC Silicon)
- Silane from SiO2 and silane pyrolysis in fluid bed (Ethyl Corp – MEMC)
- Direct reduction and purification (metallurgical route, Elkem,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



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

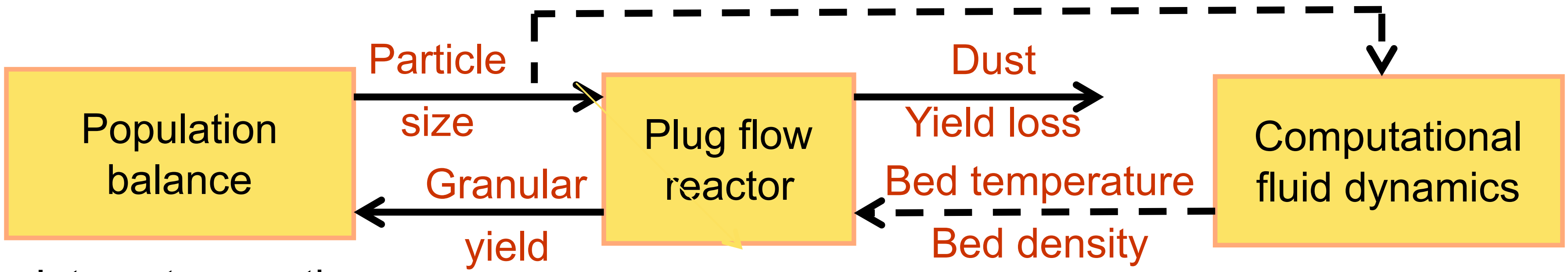
$$SiH_{4(g)} \rightarrow Si_{(s)} + 2H_{2(g)}$$

increase throughput
Reduce energy cost



Fluid Bed Reactor
Continuous Process
Large surface area
650?C

Multi-scale model for Scale-up and Design



Integrate over time for particle size distribution

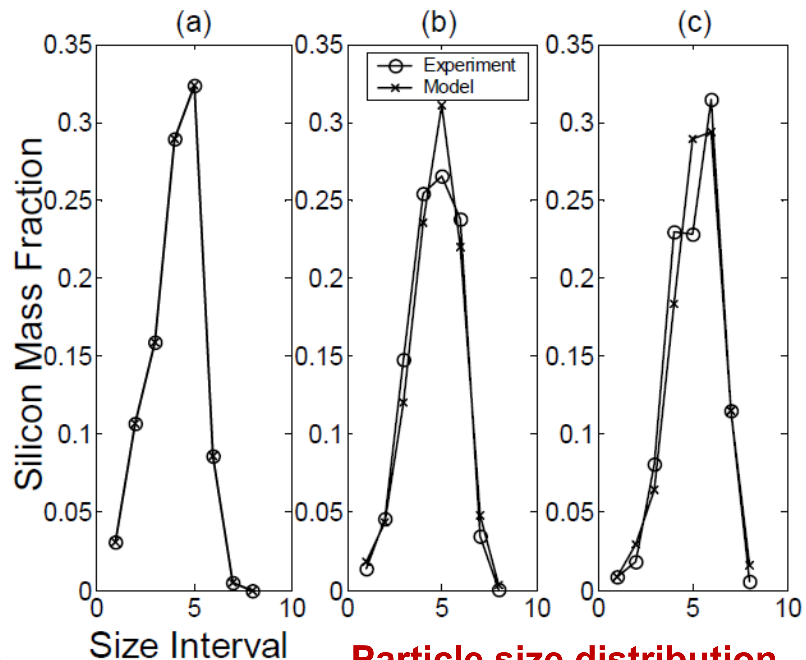
Integrate over height for granular yield

Simulate 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*



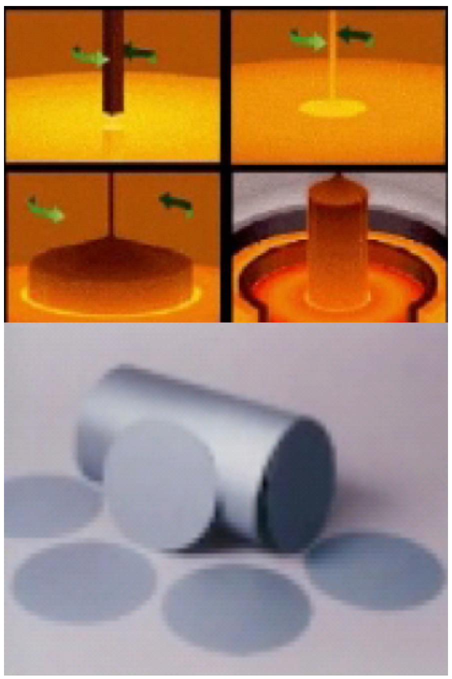
Particle size distribution Model vs Experiments

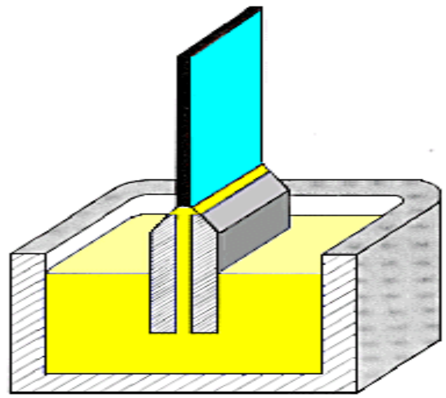
Commercial Process Built in 2009

Silicon Wafers using Float Process

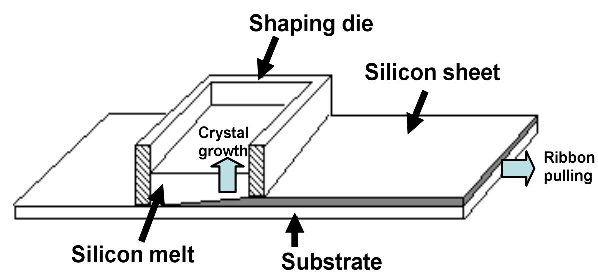
Current methods are carried out in batch
Continuous processes yield inferior product

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





Edge-Defined Film Fed Growth (EFG)



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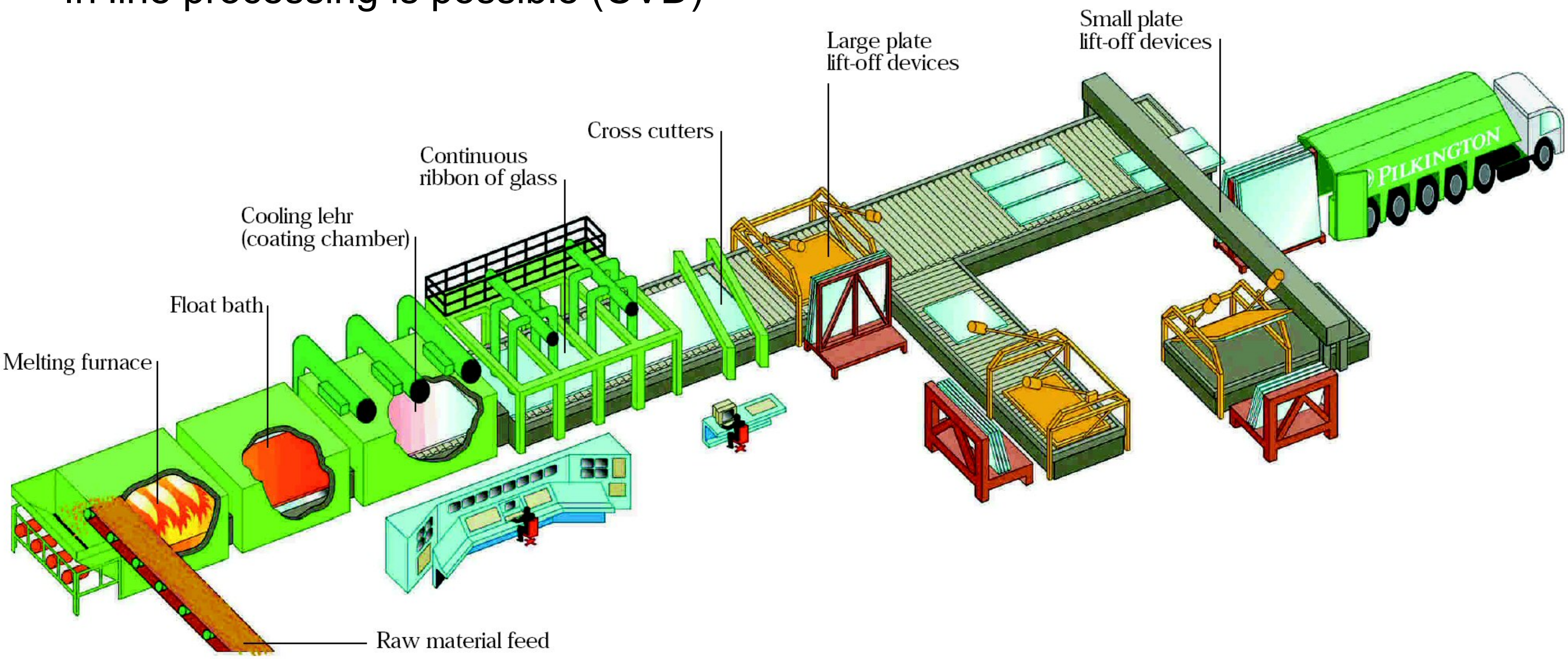
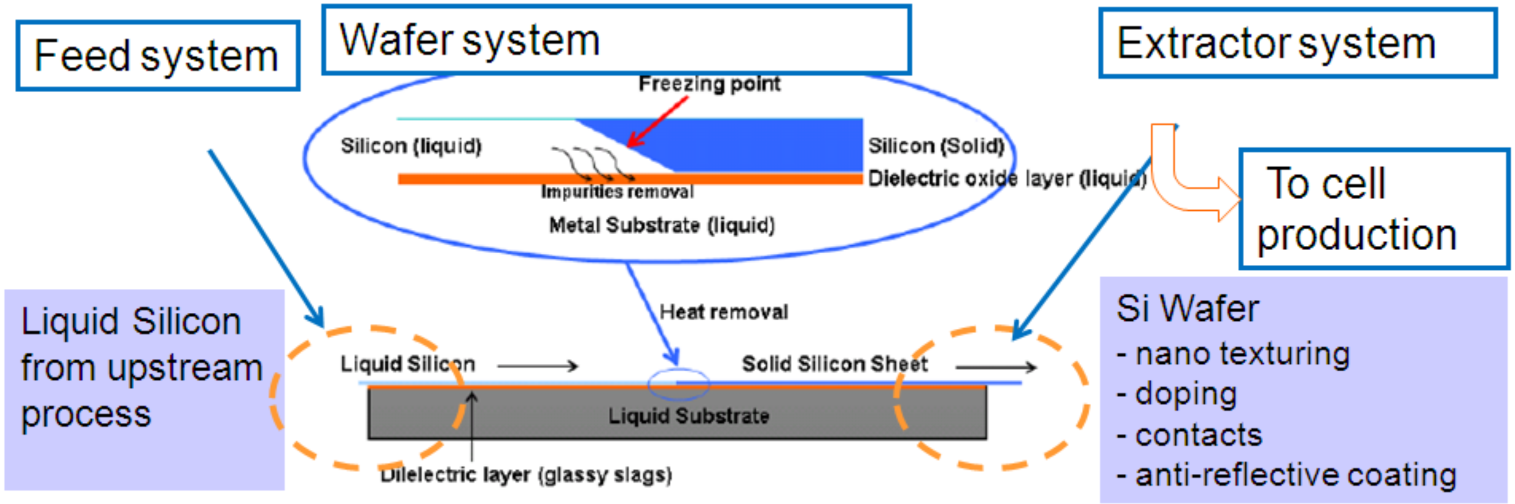
The Pilkington float Glass Process

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

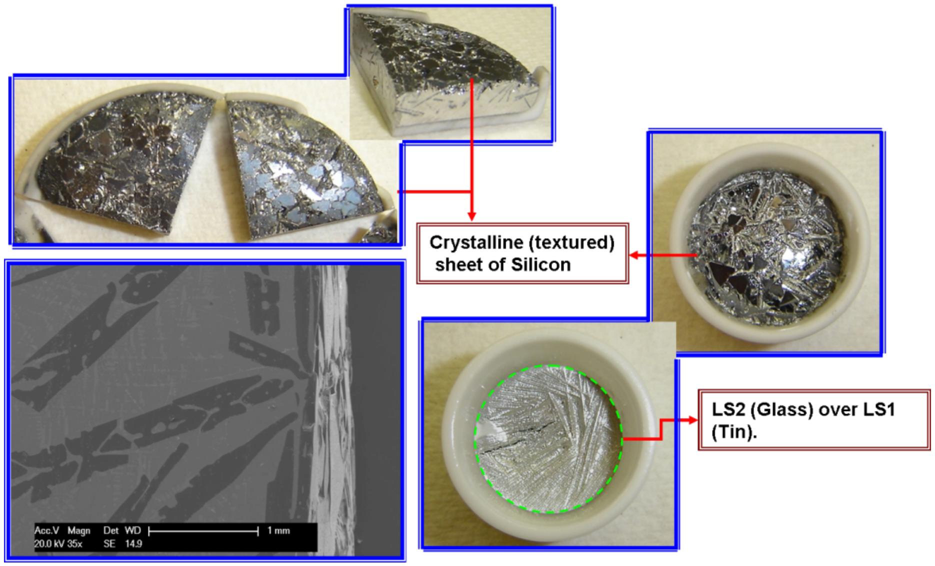


2009-2013 NSF grants* to study

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

Experimental Proof of Concept

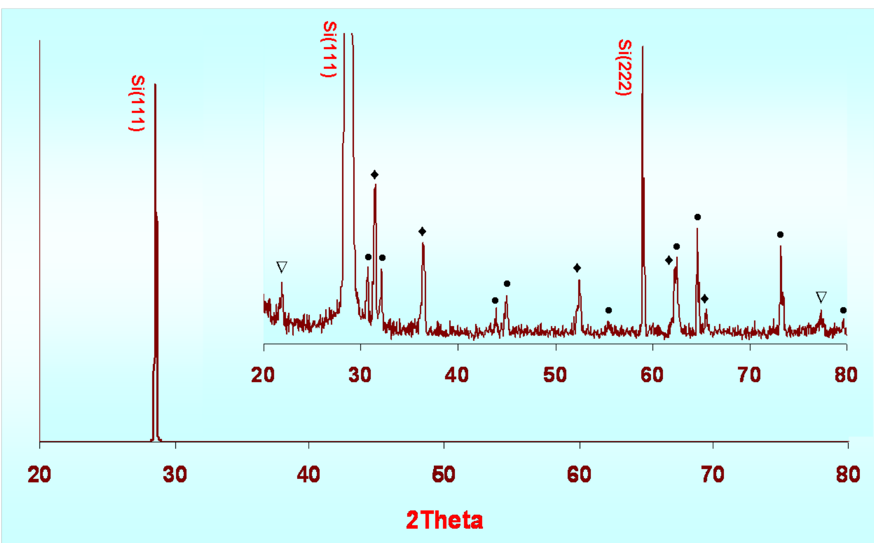


❖ Simulations show that the Silicon melt has to be floated on the substrate and the temperature should be maintained such that there is a liquid layer between the solidified Silicon and the substrate.

❖ The criteria is satisfied experimentally,[3] 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 (∇), Lead (♦) and Tin (•).

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

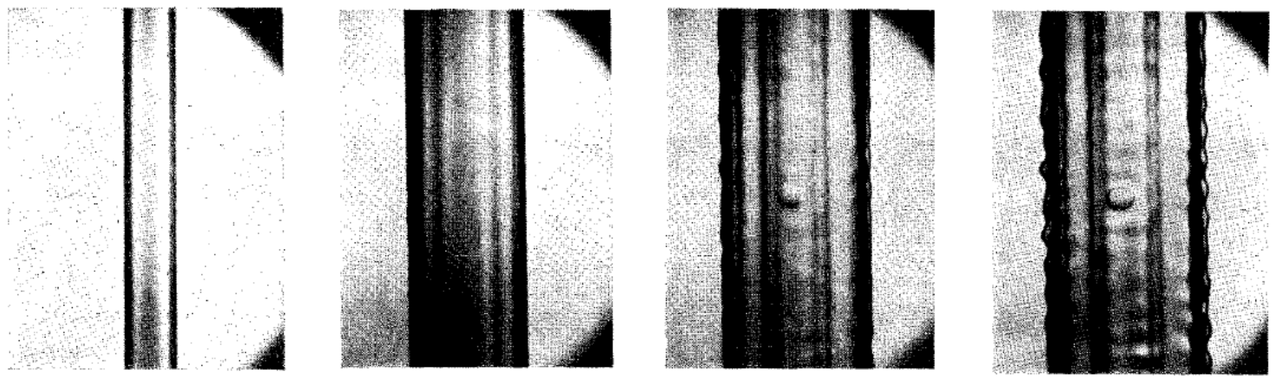
[3]US Patent - Patent Pending (2008) "Casting of Solar Quality Silicon Sheet (or Wafer) by Float Process".

Mullins-Sekerka Instability –Spherical Instability

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

Concentration gradient **favors growth** of harmonic

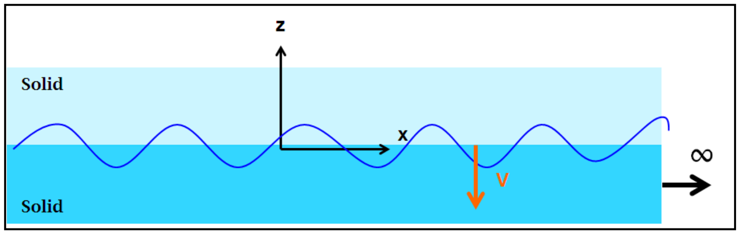
Capillary effect **favors decay** of harmonic

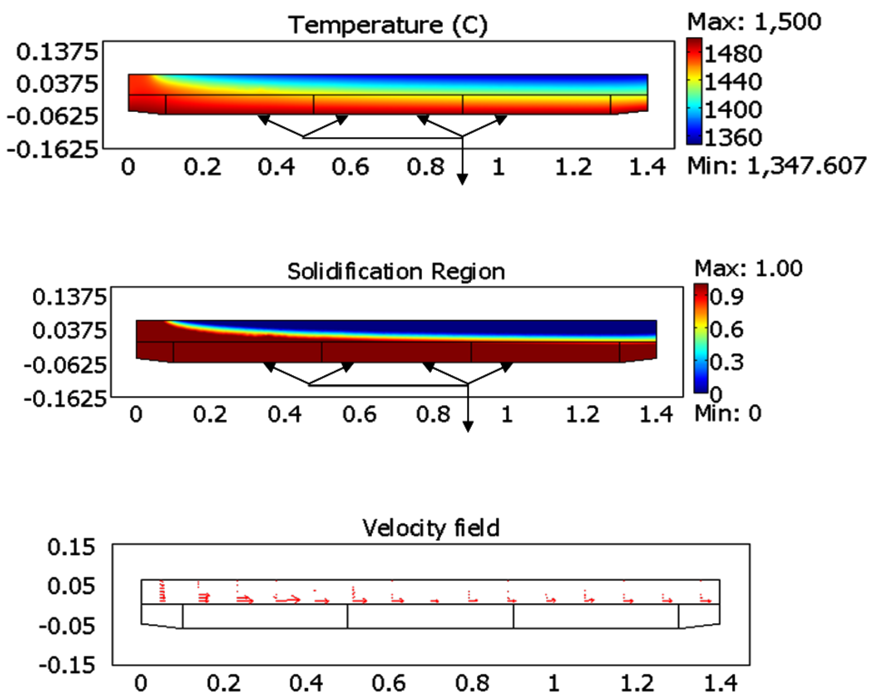


(a) (b) (c) (d)

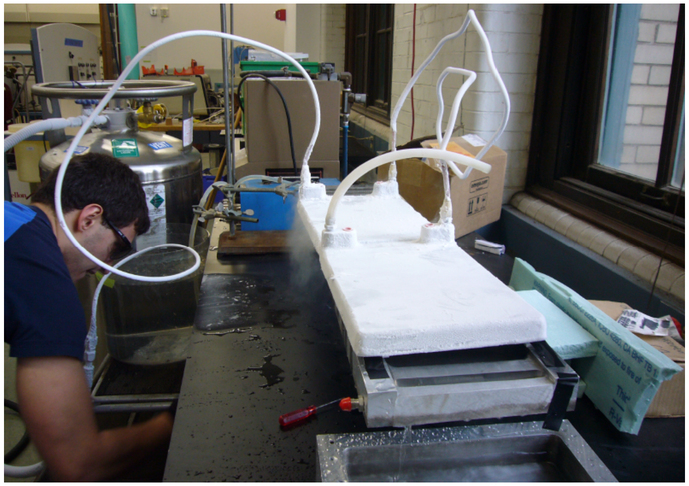
Stability of Float Process for Silicon Wafers

Theory: Stability and process modeling

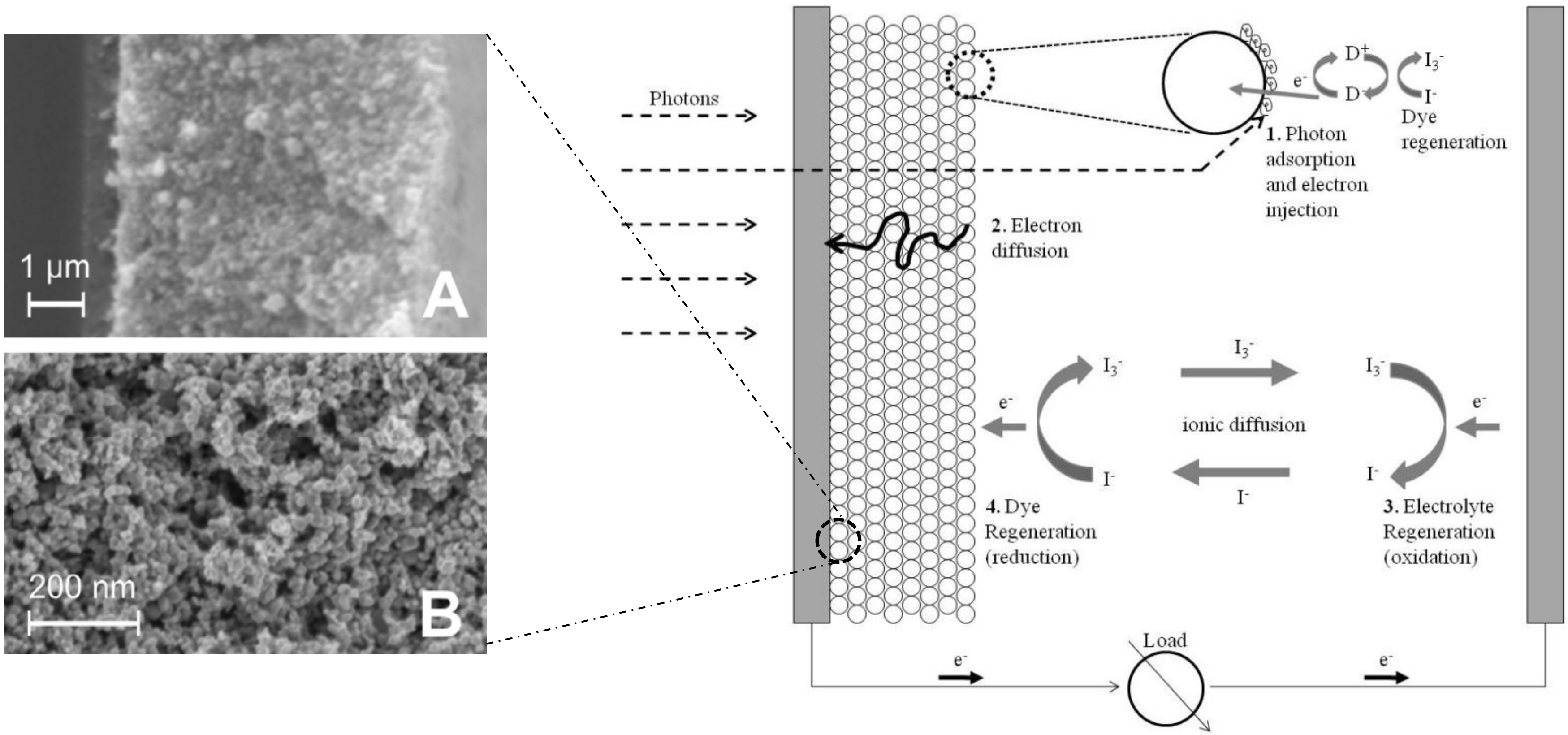




Experiments: Water models



Dye Sensitized Solar Cells (DSC)



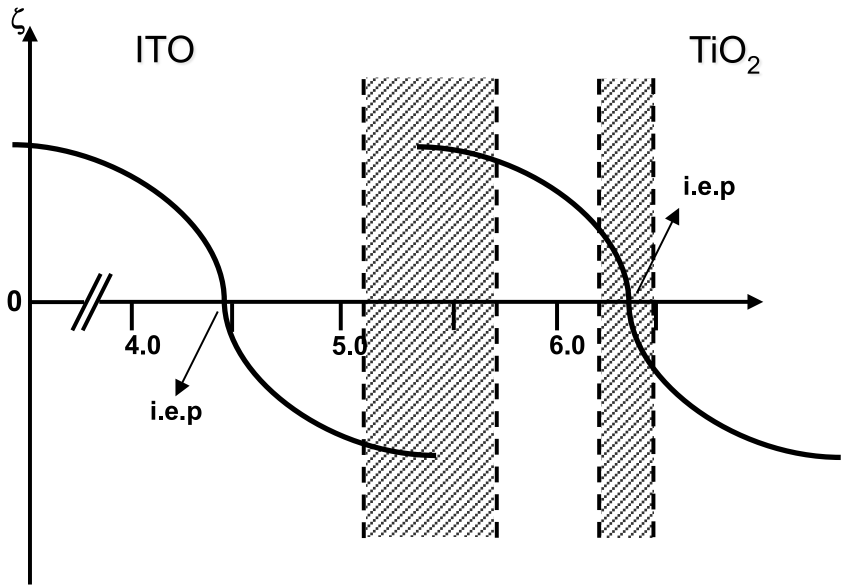
- -First shown in labs circa 1991 by Gratzel et al[1]
- -3rd generation solar cell, utilizing a thin film of TiO_2 nanoparticles
- -TiO_2 particles, coated with a dye, act as the photoanode
- -Materials are inexpensive, but only low efficiencies are possible without costly processing

1. B. O'Reagan, M. Gratzel, *Nature* 335 (1991) 737

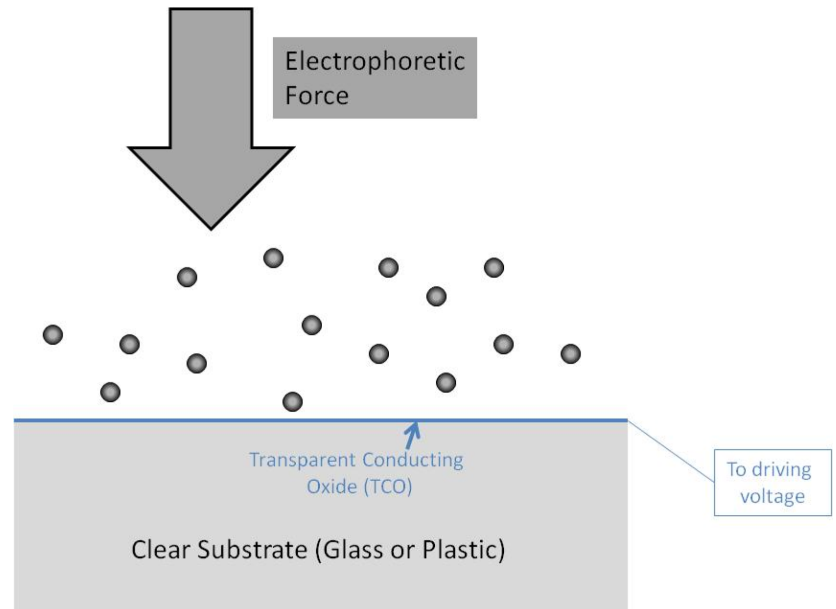
Photo: U. Opara Krasovec et al. *Solar Energy Materials and Solar Cells*. 93 (2009) 379-381

Ordered TiO2 Layer

Colloid and Surface Science



Electrophoresis and Electrochemistry



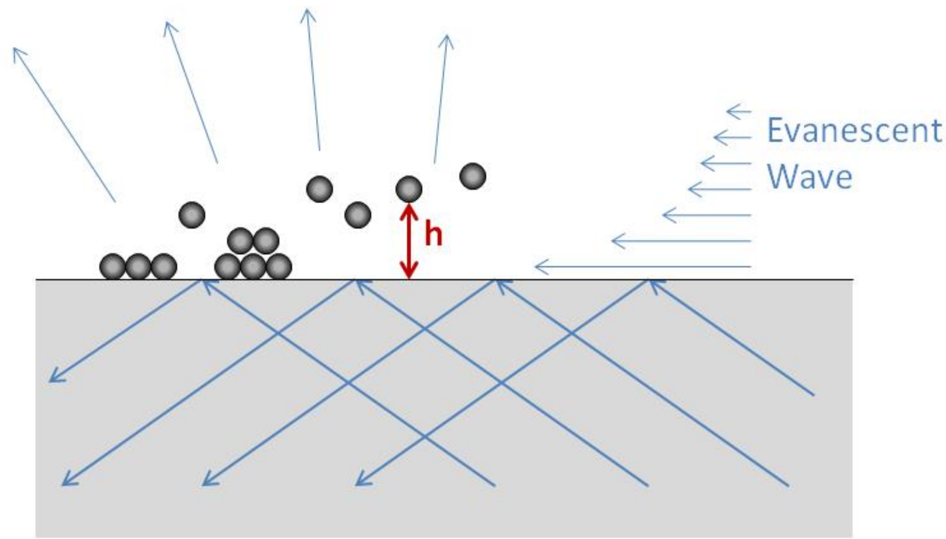
Intention – to use surface science and electrochemistry to create an ordered layer

- reduce distance through which electrons must migrate
- Layer should be sufficiently conductive without sintering at 450° C, enabling the use of plastic substrates

In-situ Monitoring – Kinetics and Process Study

Evanescent wave scattering allows us to observe the presence, approach, and departure of particles from a surface, enabling deeper insights into then 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.

$$I(h) = I_0 \exp(-\beta h)$$



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