Wafer Silicon-Based Solar Cells

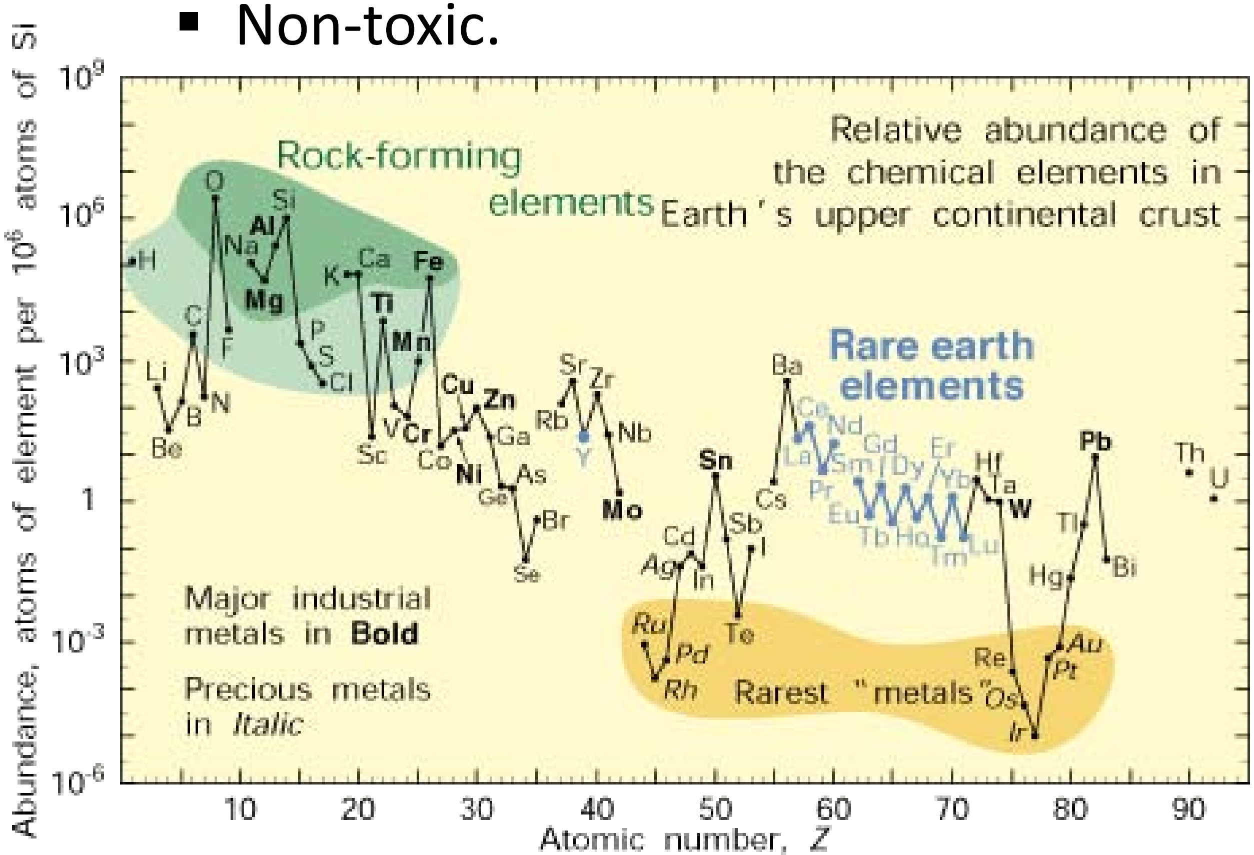
Lectures 10 and 11 – Oct. 13 & 18, 2011
MIT Fundamentals of Photovoltaics 2.626/2.627
Prof. Tonio Buonassisi

Silicon-Based Solar Cells Tutorial

- Why Silicon?
- Current Manufacturing Methods
- Next-Gen Silicon Technologies

Rationale for Si-based PV

- Scalability:
  - Earth abundance of Si. Capable of reaching TW scales.
  - Non-toxic.



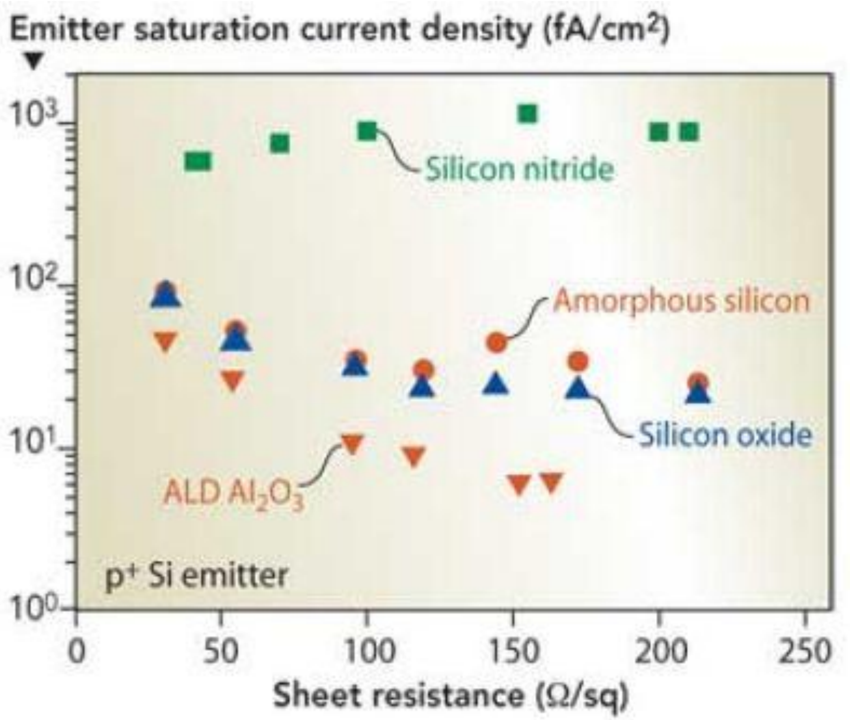
"If you want solar cells dirt cheap, you have to make them out of dirt."

Inspired by a quote Prof. Donald Sadoway applies to batteries.

Source: U.S. Geological Survey Fact Sheet 087-02
Available online: http://pubs.usgs.gov/fs/2002/fs087-02/

Rationale for Si-based PV

- Passivating Oxide Layer
  - Low surface recombination velocity.
  - Effective diffusion barrier



Courtesy of Chris Hodson and Erwin Kessels. Used with permission.

http://www.pennenergy.com/index/power/display/7519461660/articles/Photovoltaics-World/volume-2009/Issue_4/features/minimizing-losses.html

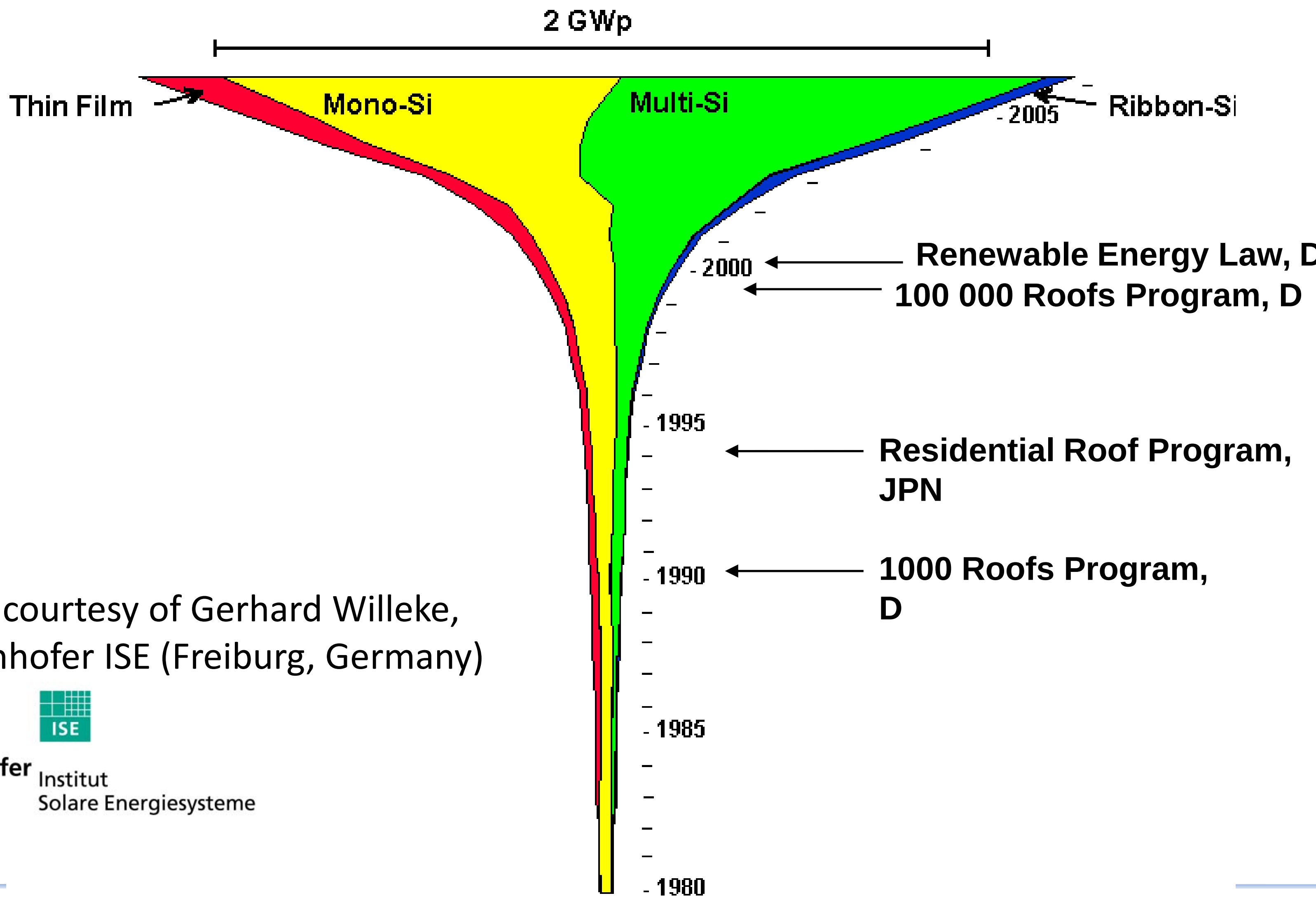
Rationale for Si-based PV

- Momentum:
  - Most common semiconductor material
  - 50+ years of manufacturing and R&D experience
  - $50B industry today
  - Technology acceptance results in low interest rates

Silicon-Based Solar Cells Tutorial

- Why Silicon?
- Current Manufacturing Methods
  - Overview: Market Shares
  - Feedstock Refining
  - Wafer Fabrication
  - Cell Manufacturing
  - Module Manufacturing
- Next-Gen Silicon Technologies

Photovoltaics: State of the Art



Slide courtesy of Gerhard Willeke, Fraunhofer ISE (Freiburg, Germany)

Fraunhofer Institut Solare Energiesysteme

Silicon-Based Solar Cells Tutorial

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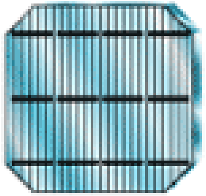
Si-based PV Production: From Sand to Systems

Feedstock Refining

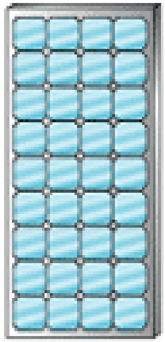
Raw Materials

Si Feedstock

Wafer



Cell



Module

System

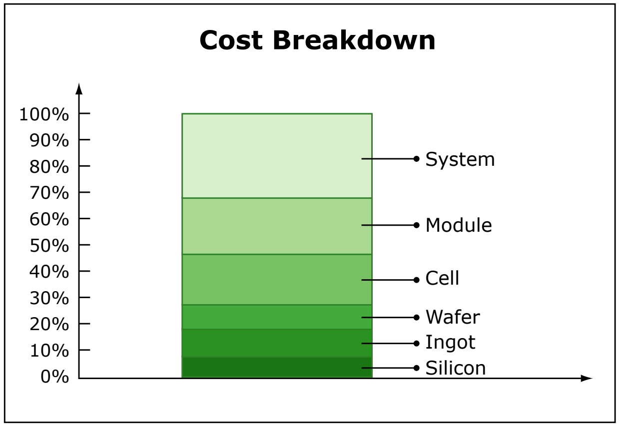


Image by MIT OpenCourseWare. After H. Aulich, PV Crystalox Solar.

Step 1: Metallurgical-Grade Silicon (MG-Si) Production

For MG-Si production visuals, please see the lecture 10 video.

From: Handbook of PV Science and Technology, available online at www.knovel.com

MG-Si Market

- Approx. 1.5–2M metric tons of MG-Si produced annually.[1]
- ~6% of MG-Si produced annually is destined for PV. The remainder goes to the IC industry (~4%), silicones (~25%), metal alloys including steel and aluminum (~65%).

[1]Source: http://www.photon-magazine.com/news_archiv/details.aspx?cat=News_PI&sub=worldwide&pub=4&parent=1555

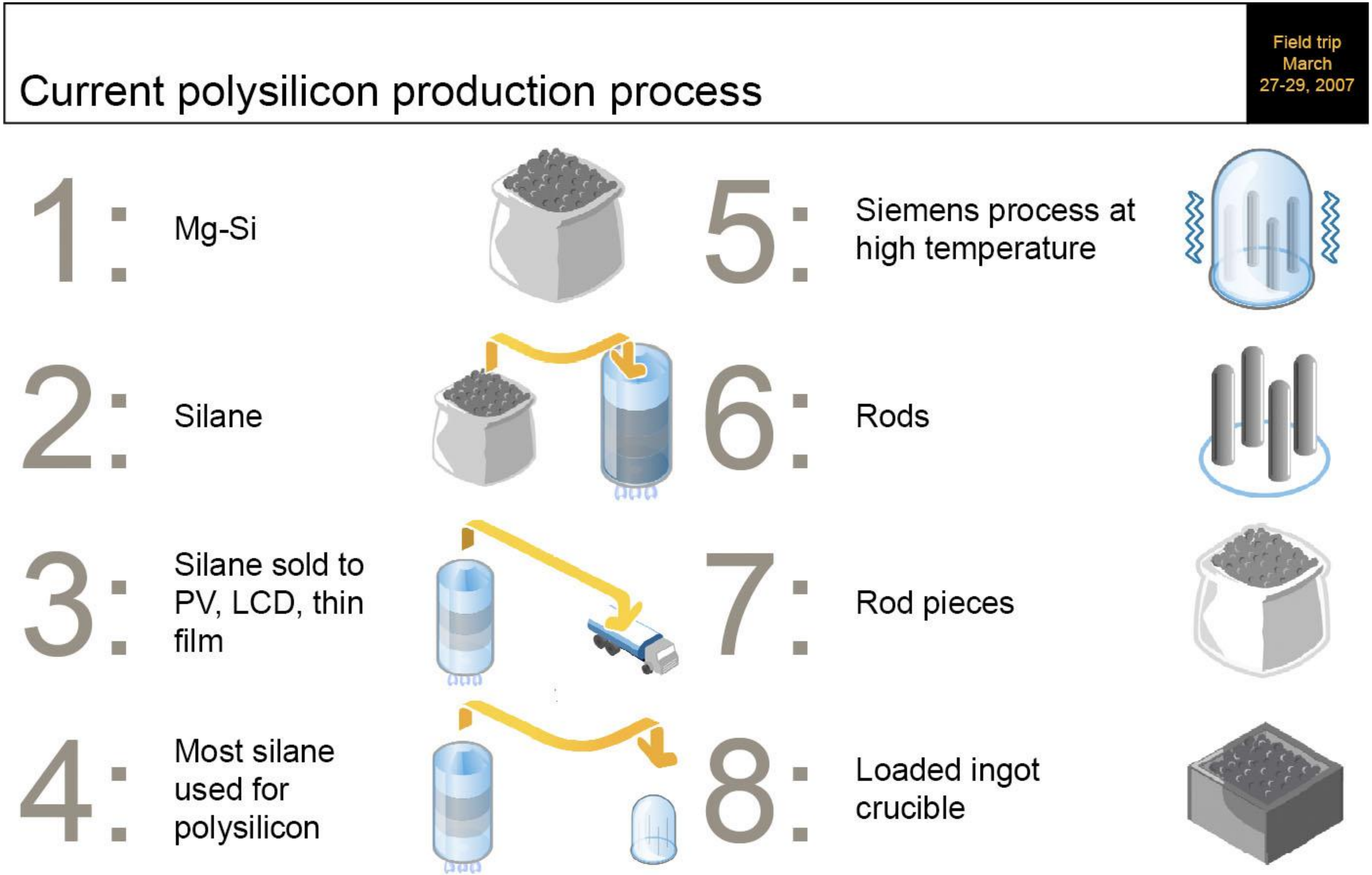
MG-Si Outlook

- PV is the fastest-growing segment of the MG-Si market (approx. 40%/yr).
- Approx. 2 kg of MG-Si are used to make 1 kg of refined silicon.
- Additional refining capacity needed to keep up with PV growth.

Standard Silicon Feedstock Refining Process: The "Siemens Process"

(purification through gaseous distillation)

Step 2: Semiconductor-Grade Silicon Production



Silane Production

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See the lecture 10 video for this content.

Image Source: REC

PolySi Production

- Traditionally very high purity (9N, or ~99.9999999%), appropriate for the semiconductor industry.
- Recently, process adjusted for lower cost, resulting in 6N Solar-Grade Silicon (SoG-Si)

Image Source: REC

Scale: Large Plants, Long Lead Times

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See the lecture 10 video for this content.

Source: REC

- Lead time for new factory: typically 18-24 months
- Investment: 100's of M$.

PolySi Outlook

- Scale: Poly-Si production ~120,000 MT/year (over half for PV industry).
- Cost ~ 25 $/kg
  - *2010 Price ~ 50-70 $/kg (long-term contracts)*
  - *2008 Price ~ 500 $/kg (spot market)*
- Slow response to changing demand: Long leadtimes and large cost of capacity expansion result in oscillatory periods of over-supply and under-supply.

Alternative Solar-Grade Silicon Feedstock Refining Processes

- Fluidized Bed Reactor (FBR)
- Upgraded Metallurgical-Grade Silicon (UMG-Si): Purification through liquid route.

FBR: Fluidized Bed Reactor

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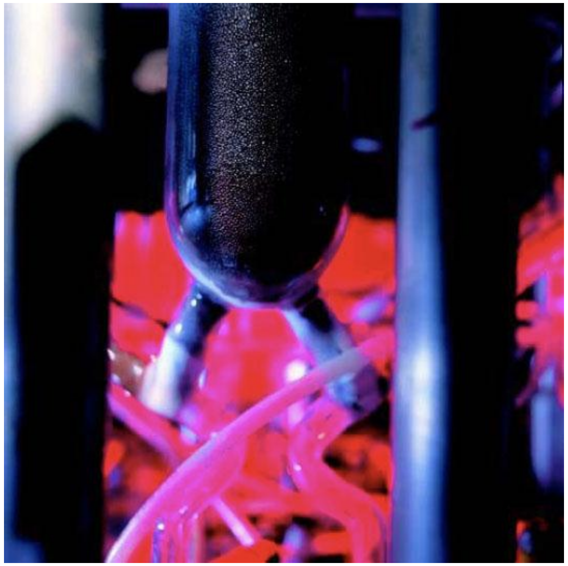
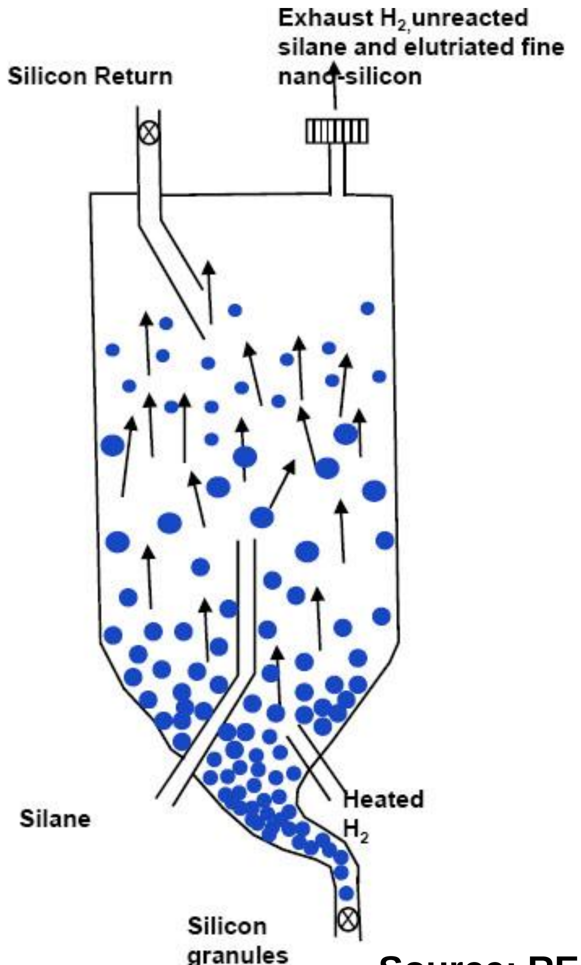


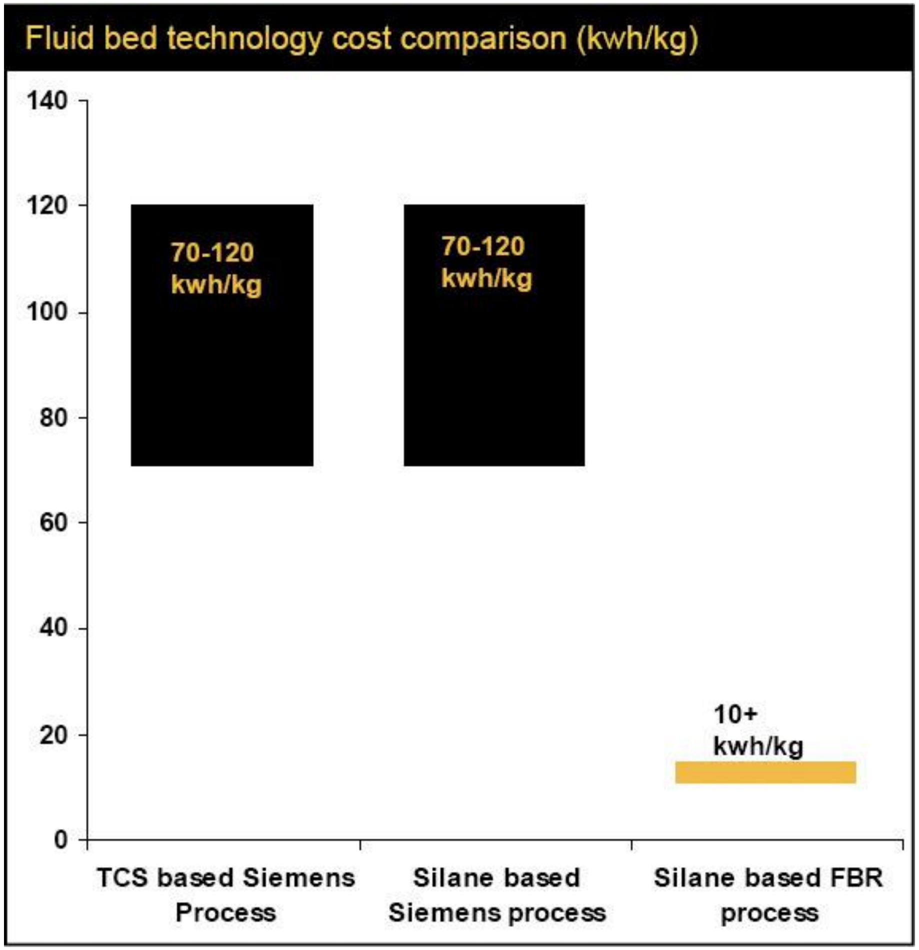
Source: REC

Advantage: Smaller seeds, larger surface area/volume ratio, faster deposition!

FBR: Fluidized Bed Reactor

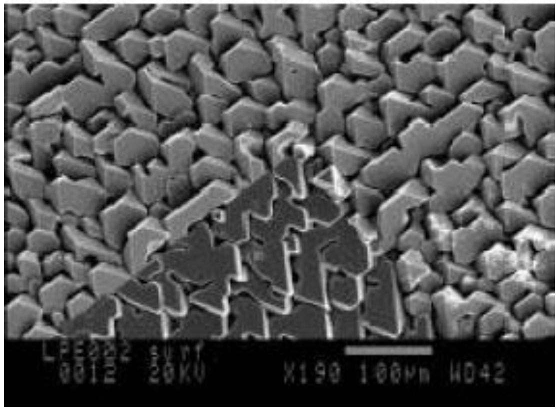


Source: REC



Upgraded Metallurgical-Grade Silicon (UMG-Si)

- Distinguished by liquid-phase purification

Slag Refining	Leaching	Solidification
		

Source: REC

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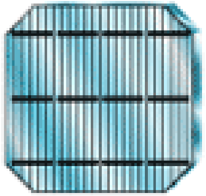
Si-based PV Production: From Sand to Systems

Crystal Growth / Wafer Fab

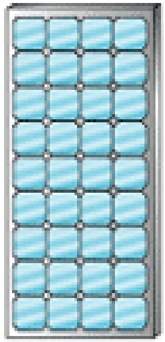
Raw Materials

Si Feedstock

Wafer

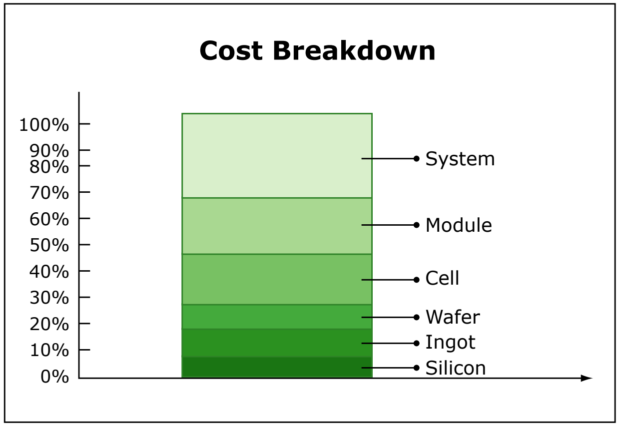


Cell



Module

System



Crystalline Silicon Wafer Technologies Used in PV

- Single-crystalline ingot growth (~35% of market)
  - *Mainly Czochralski, and some Float Zone.*

- Casting of multicrystalline silicon ingots (~50% of market)

- Ribbon growth of multicrystalline silicon (~1% of market)

- Sheet growth of multicrystalline silicon (~0% of market)

Czochralski Growth

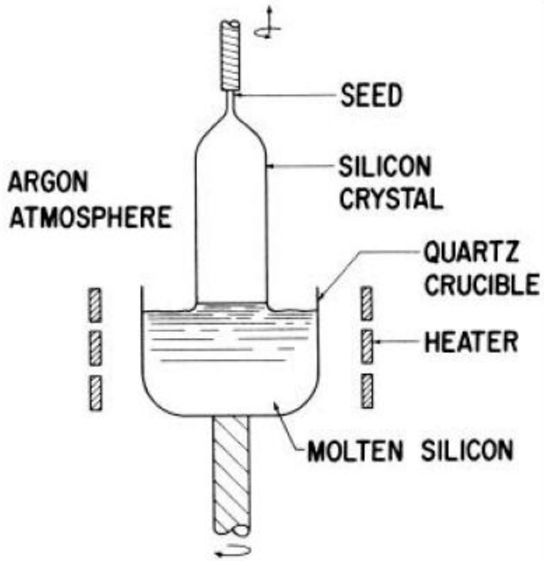
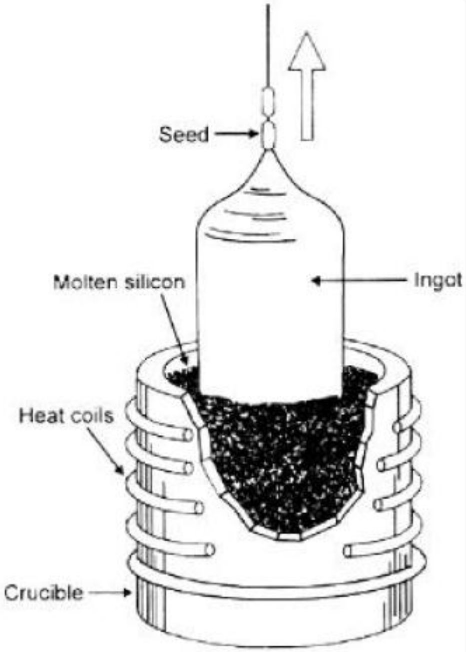


FIGURE 1. CZOCHRALSKI CRYSTAL GROWTH PROCESS



1916, Polish physicist Jan Czochralski

Si melting point 1414°C

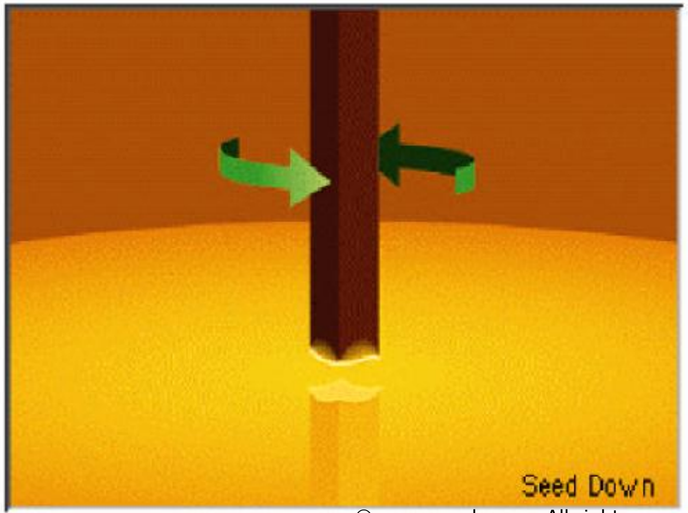
Growth rate approx. 5 cm/hour

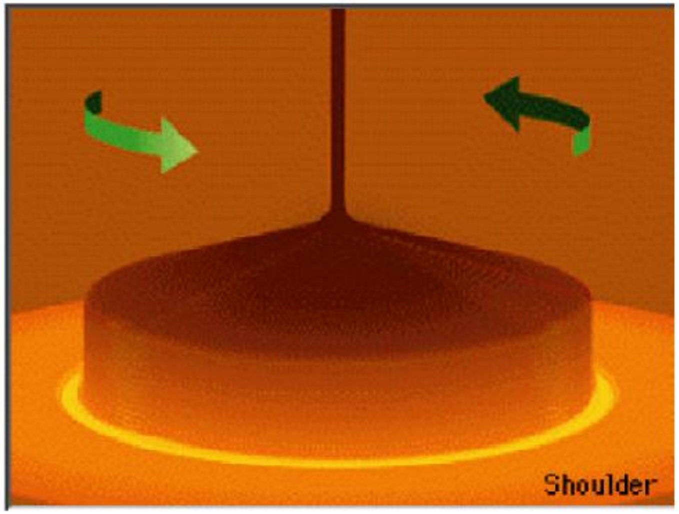
Typical crystal size:
10-30 cm in diameter,
1-2 meters long

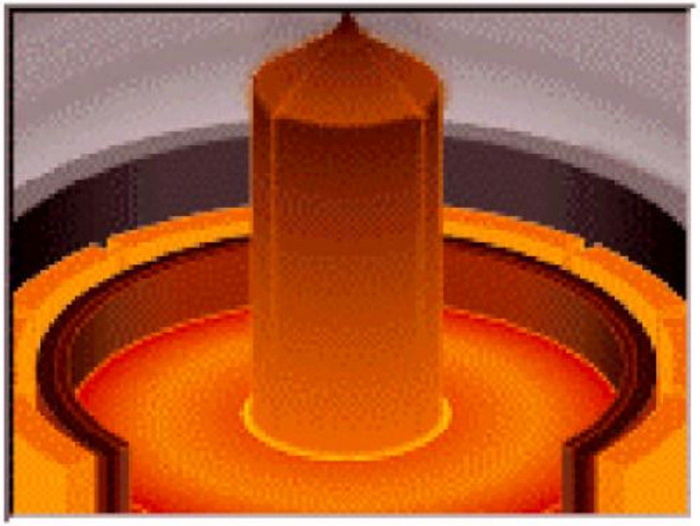
This type of silicon is the standard for integrated circuit industry. Very high quality ingots. Partial dissolution of quartz crucible introduces oxygen and carbon into the melt.

Slide courtesy of A. A. Istratov. Used with permission.

Principles of the CZ Growth Process







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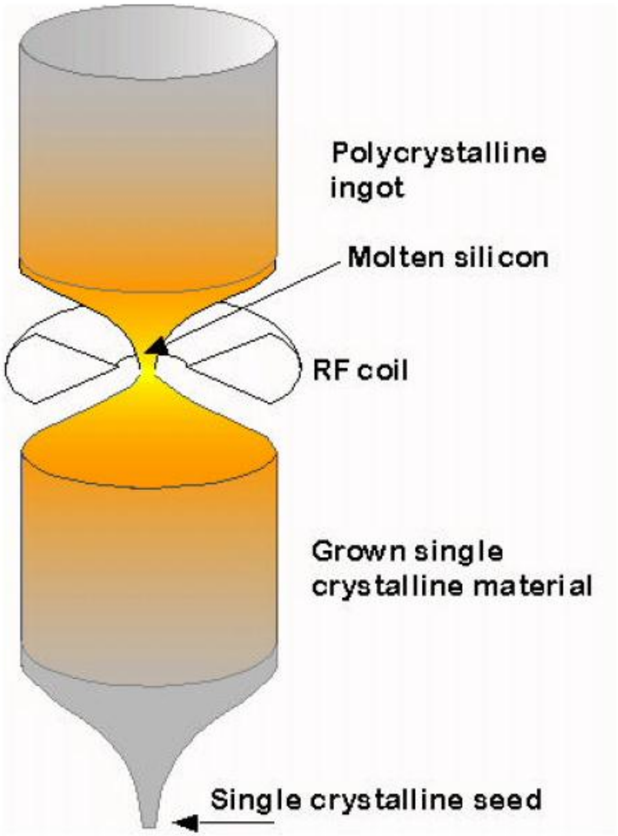
Float-Zone Growth



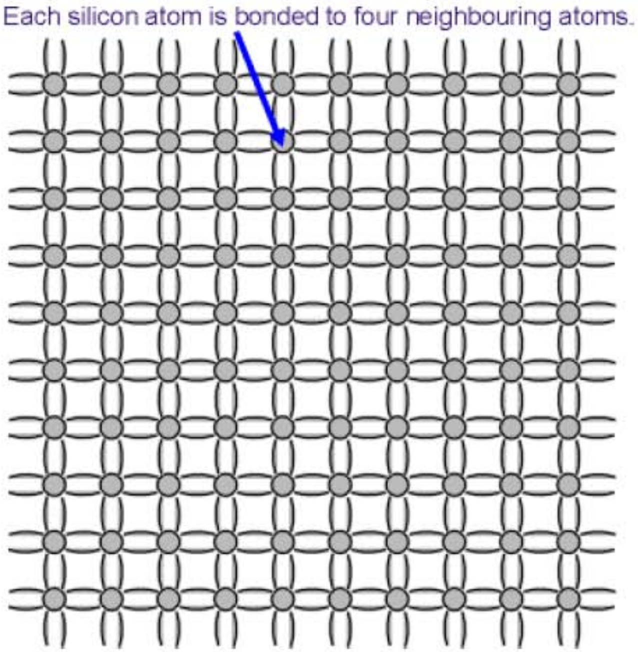
Diameters and rotation speeds of the polysilicon ingot and the growing single crystals can be different

Crystal grows without contact with crucible and has the lowest possible impurity content (particularly low oxygen and carbon content). However, FZ growth appears to be more expensive than CZ growth and is used only for the most demanding applications.

Crystalline Silicon

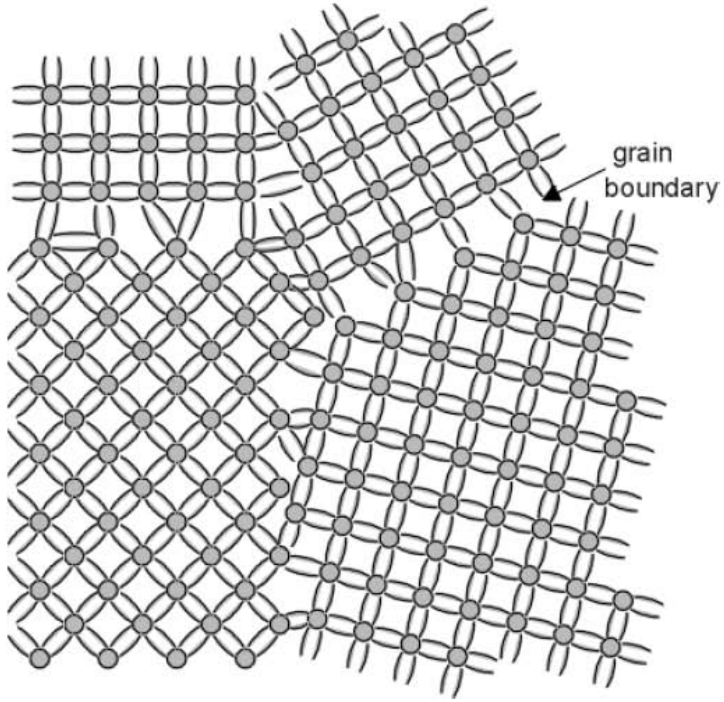
Single crystalline silicon

FZ, CZ



Multicrystalline silicon

Cast, ribbon, sheet techniques



Courtesy of PVCDROM. Used with permission.

The grain size in multicrystalline silicon is from several microns to several millimeters or even centimeters. The fundamental physical properties such as bandgap and absorption properties are similar. The difference between c-Si and mc-Si is primarily the density of defects and impurities – and **cost, cost, cost**.

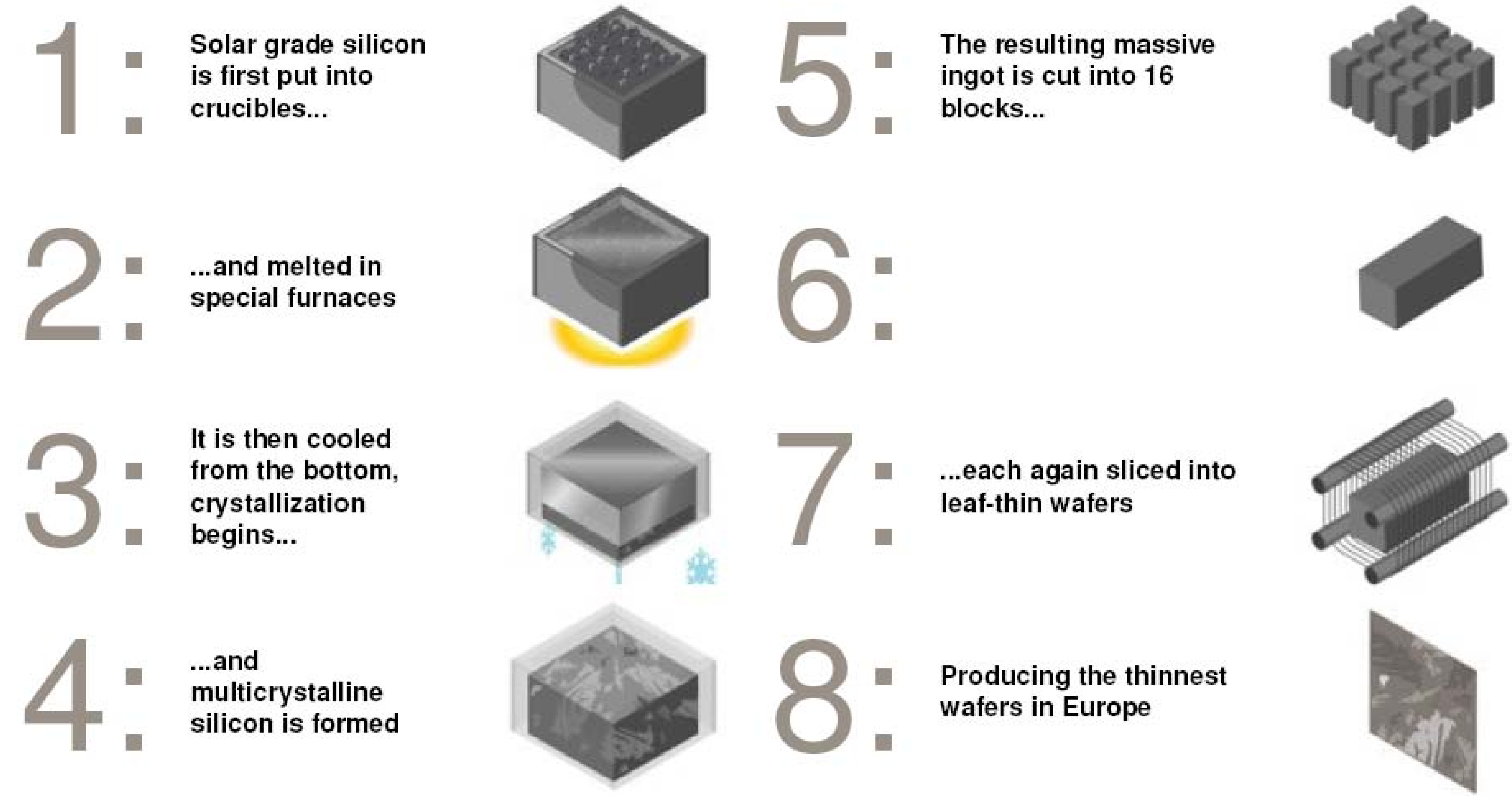
Distinguishing mc-Si from sc-Si

grains in mc-Si are clearly visible in reflected light

Single-crystalline
CZ of FZ wafer

Multicrystalline silicon wafer

Production of ingot mc-Si



Directional Solidification of mc-Si

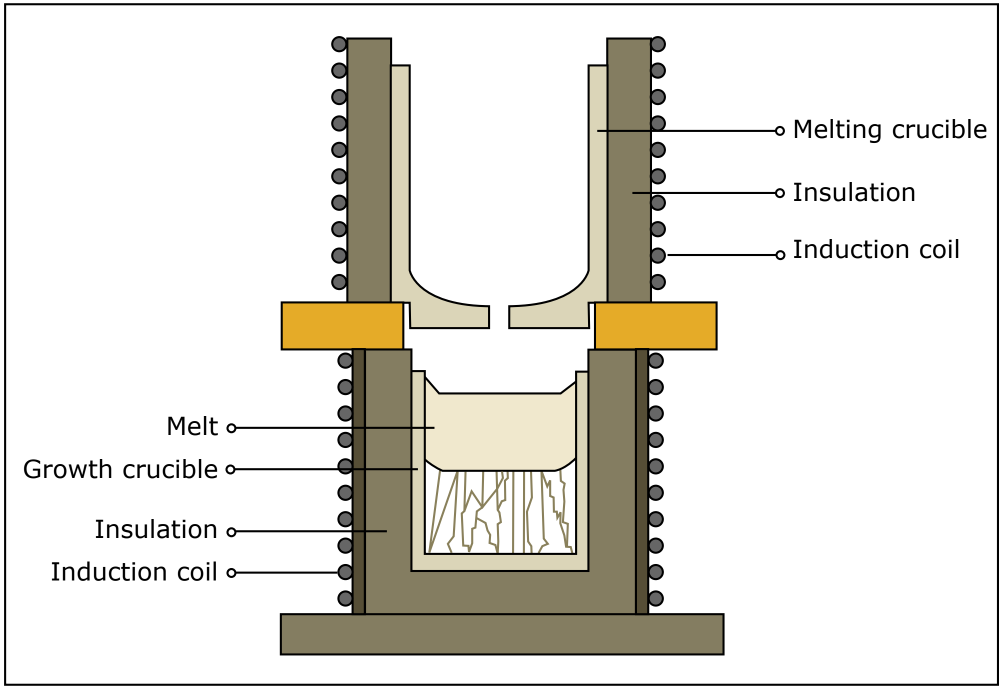


Image by MIT OpenCourseWare.

Silicon typically grown in a fused quartz crucible with Si_3N_4 coating (to prevent adhesion). Total growth times of 20-30 hours.

Ingots as large as 600 kg are entering commercial production today, with 1 tonne ingots in R&D.

Directional Solidification of mc-Si

a.k.a. Directional Solidification System (DSS), Casting, Bridgman Process.

Ingots are initially cut into rectangular blocks called “bricks,” then wire-sawed into wafers.

Please see lecture video for related furnace and brick-cutting images.

Quiz #2 Announcement

- Pre-analysis (now on Stellar): 20% of Quiz 2 grade
- $\$/W_p$ metric: 10% of Quiz 2 grade
- Solar cell efficiency analysis: 70% of Quiz 2 grade

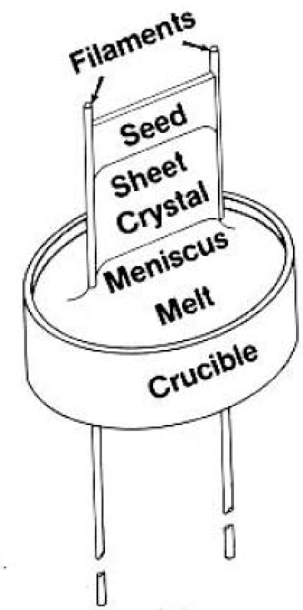
Ribbon Growth

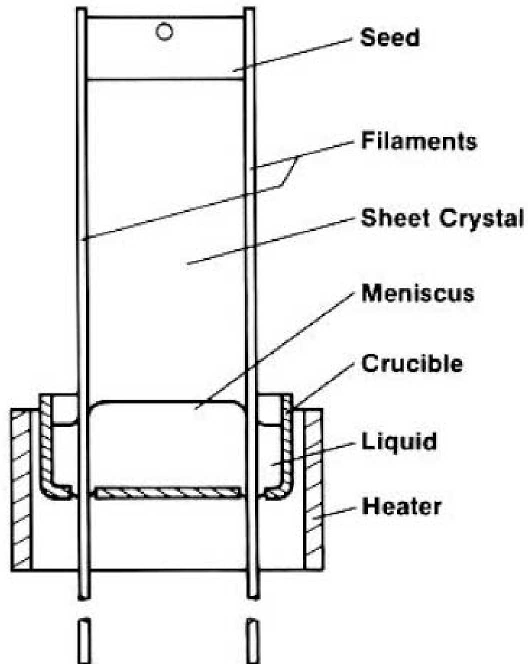
- Advantages: No kerf loss due to wire sawing, more efficient silicon utilization.
- Disadvantages: Traditionally, lower material quality → lower efficiencies. Traditionally, higher capex.

Ribbon growth of mc-Si

String Ribbon Growth Technique (Evergreen Solar, Sovello)
E. Sachs, *J. Cryst. Growth* **82** (1987) 117

Similar technique: T.F. Ciszek and J.L. Hurd, 1980: Edge-supported pulling

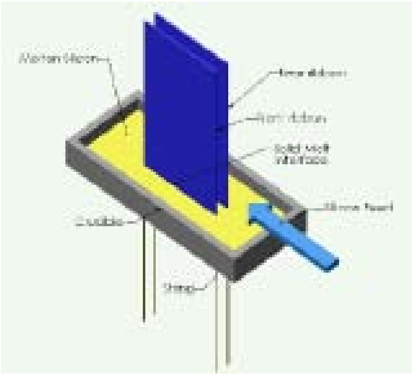


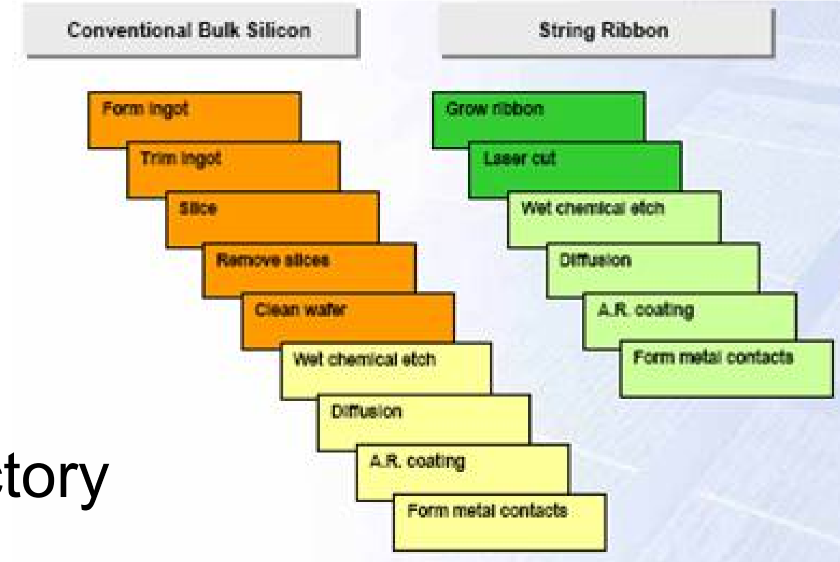


A good source of information on the basics: T.F.Ciszek, J.Cryst.Growth 66, 655 (1984).

Growth rate: 2-3 cm/min

Ribbon growth of mc-Si



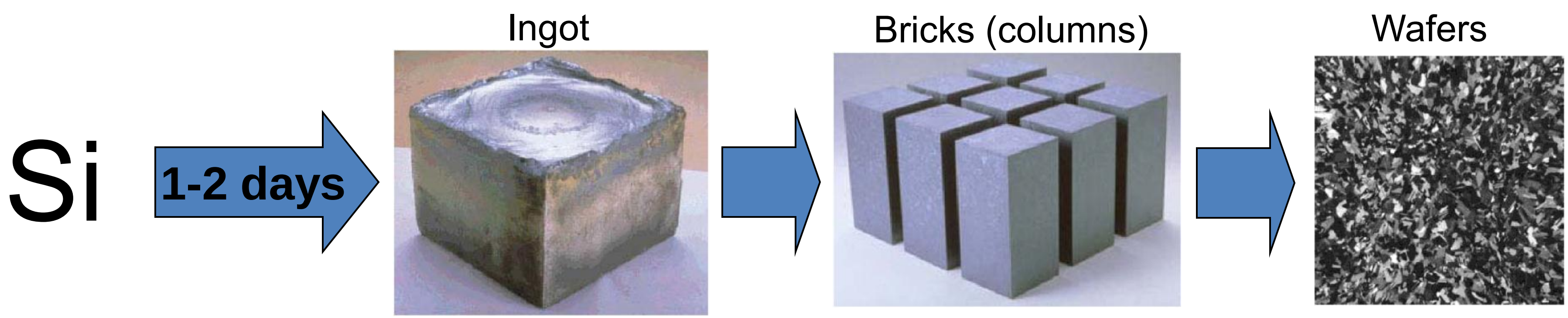


180 MW Sovello Factory

8 x 180 cm wafer; <200 microns

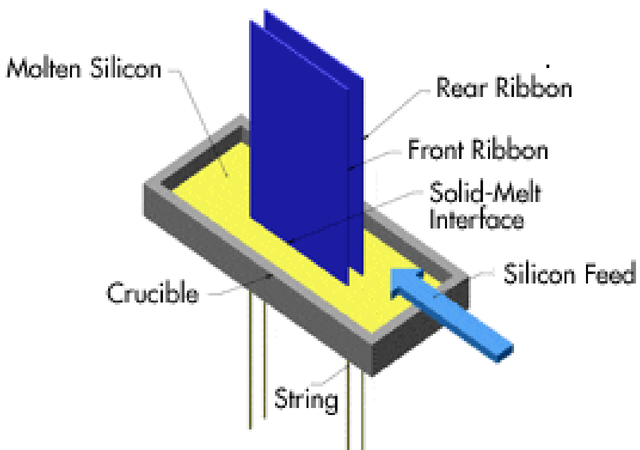
Ribbon growth of mc-Si

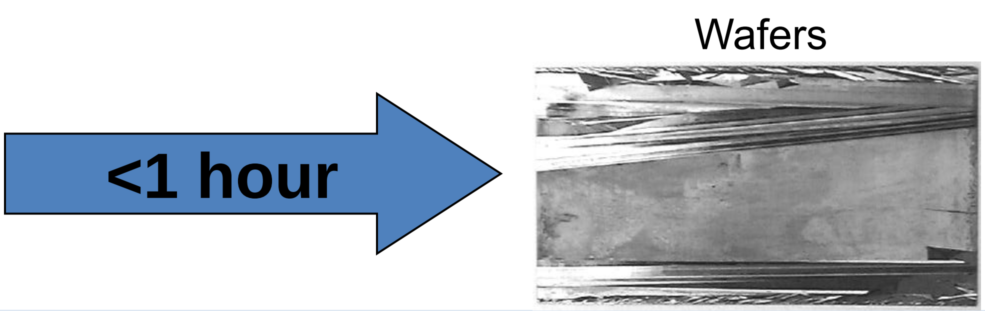
Ingot mc-Si: ~50% Si utilization



Courtesy of A. A. Istratov. Used with permission.

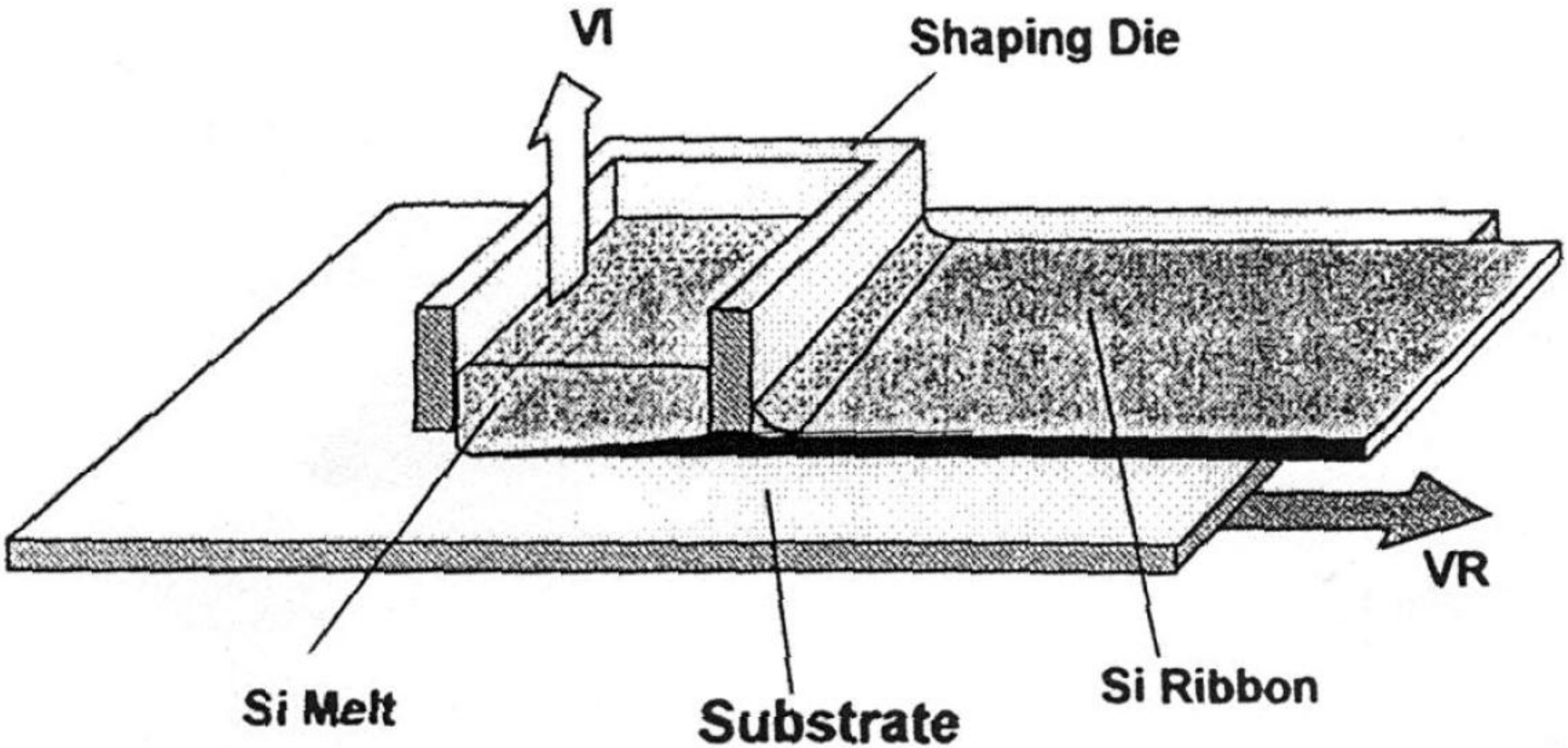
Ribbon or Sheet Growth: ~100% Si utilization





http://www.evergreensolar.com/

Sheet Growth (Horizontal Ribbon)



Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

- Schematic of Ribbon Growth on Silicon (RGS) growth process.
- 4-9 m/s pull speeds theoretically possible (VI & VR decoupled).

Wafer Fabrication: Next Directions

- Cost: Cost per watt can be reduced by:
  - *Using cheaper starting materials.*
  - *Growing/sawing thinner wafers.*
  - *Increasing furnace throughput (ingot size, growth speed).*
  - *Improving material quality.*

- Scaling Issues:
  - *Poly-Si production ~0.04M MT/year, half for semiconductor industry.*
  - *Slurry and SiC grit needed for ingot wire sawing.*
  - *50% Si loss due to wire sawing, ingot casting!*

- Technology Enablers:
  - *Use lower-quality feedstocks*
  - *Produce & handle thinner wafers*
  - *Grow faster, larger, higher-quality ingots.*

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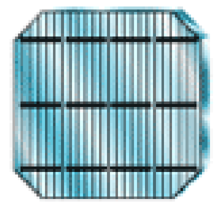
Si-based PV Production: From Sand to Systems

Cell Fabrication

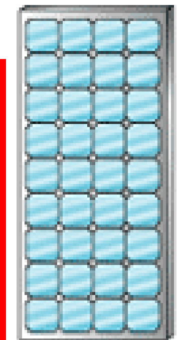
Raw Materials

Si Feedstock

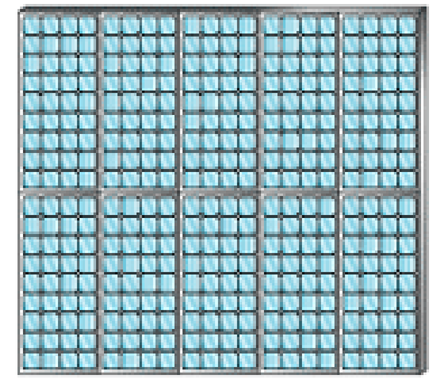
Wafer



Cell



Module



System

Public domain image.

Cost Breakdown

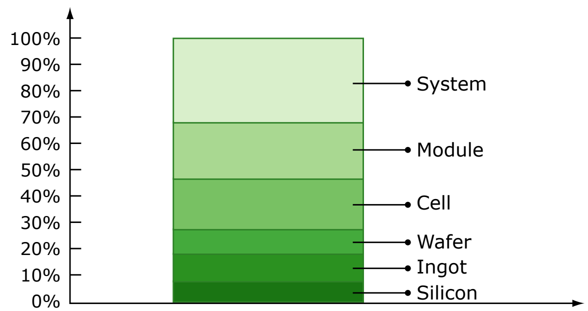
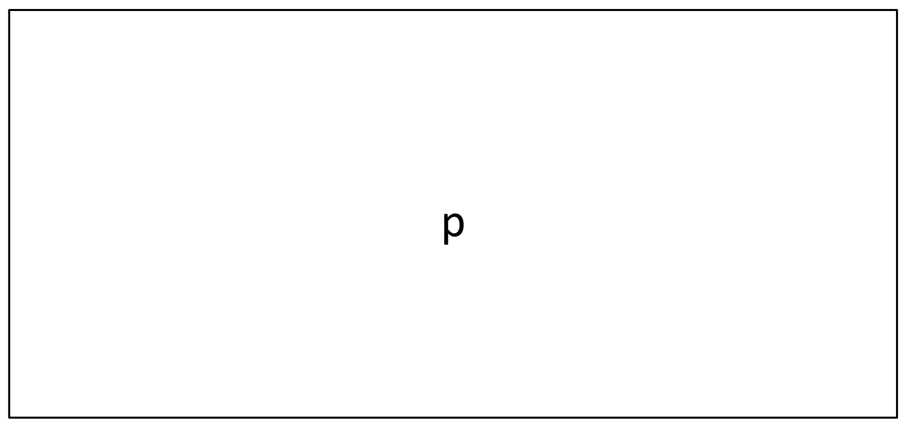


Image by MIT OpenCourseWare. After H. Aulich, PV Crystalox Solar.

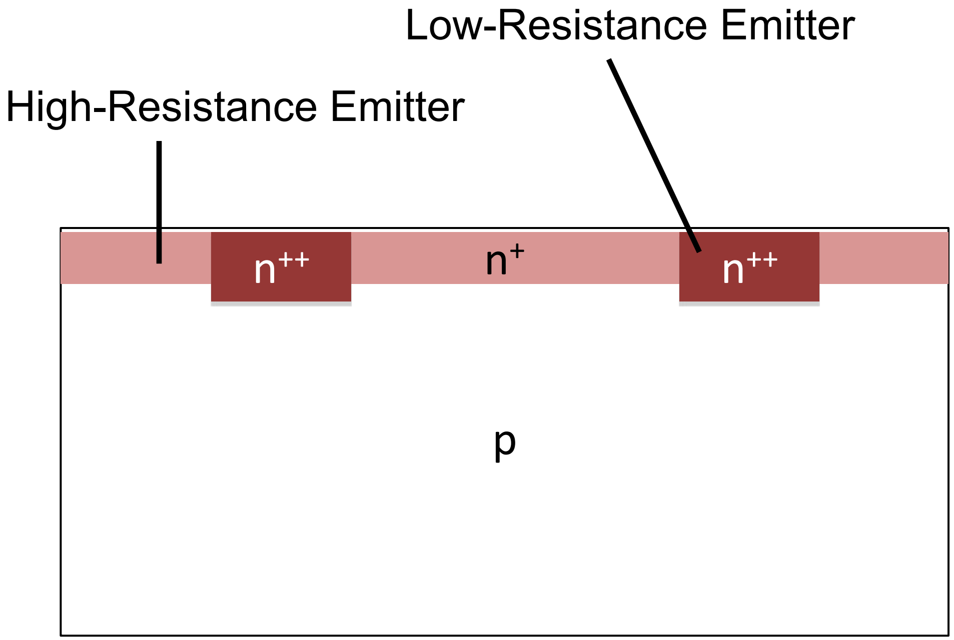
Cell Fabrication Process: State-of-the-Art

- Saw damage/texturization etch



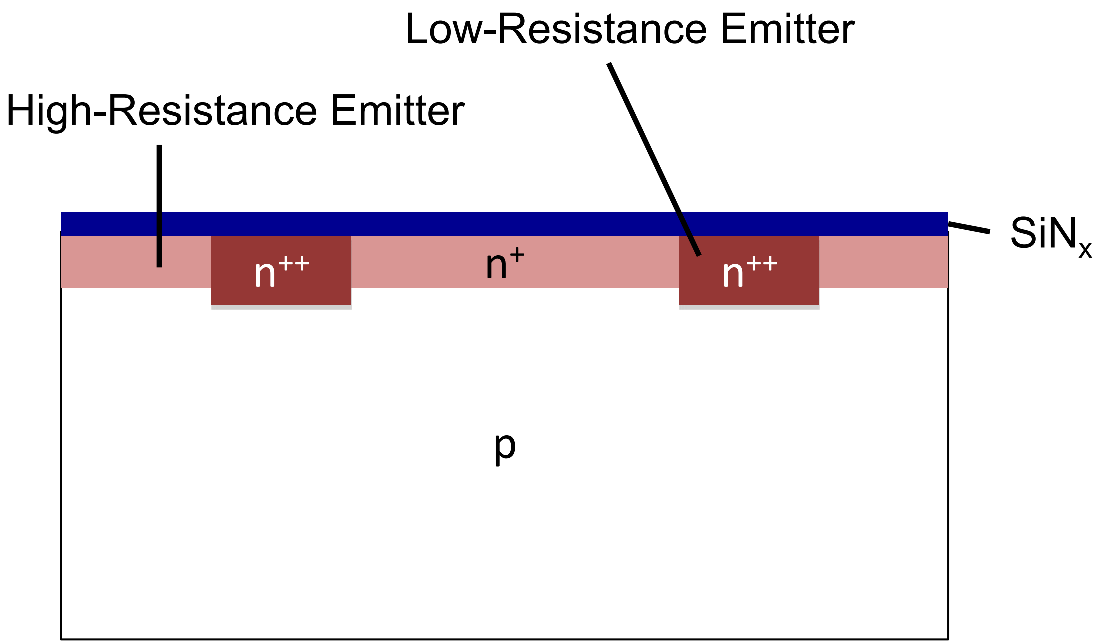
Cell Fabrication Process: State-of-the-Art

- Saw damage/texturization etch
- Selective emitter diffusion
- PSG etch



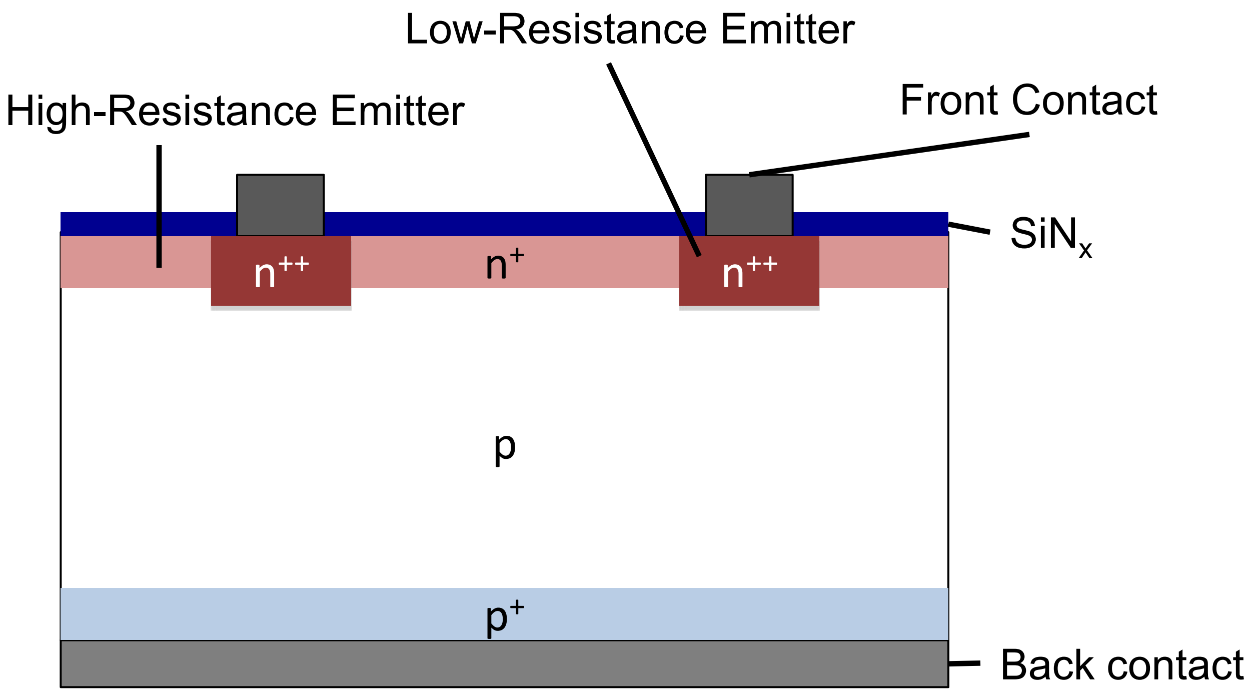
Cell Fabrication Process: State-of-the-Art

- Saw damage/texturization etch
- Selective emitter diffusion
- PSG etch
- Nitride ARC



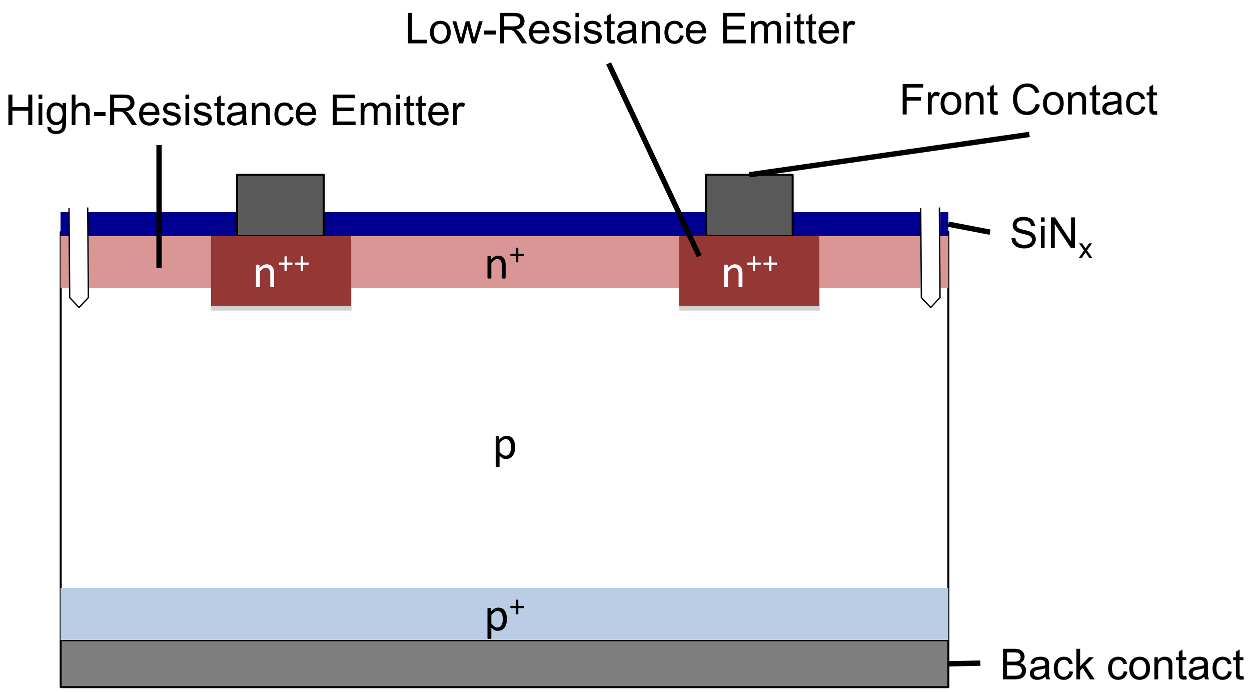
Cell Fabrication Process: State-of-the-Art

- Saw damage/texturization etch
- Selective emitter diffusion
- PSG etch
- Nitride ARC
- Metallization
- Firing

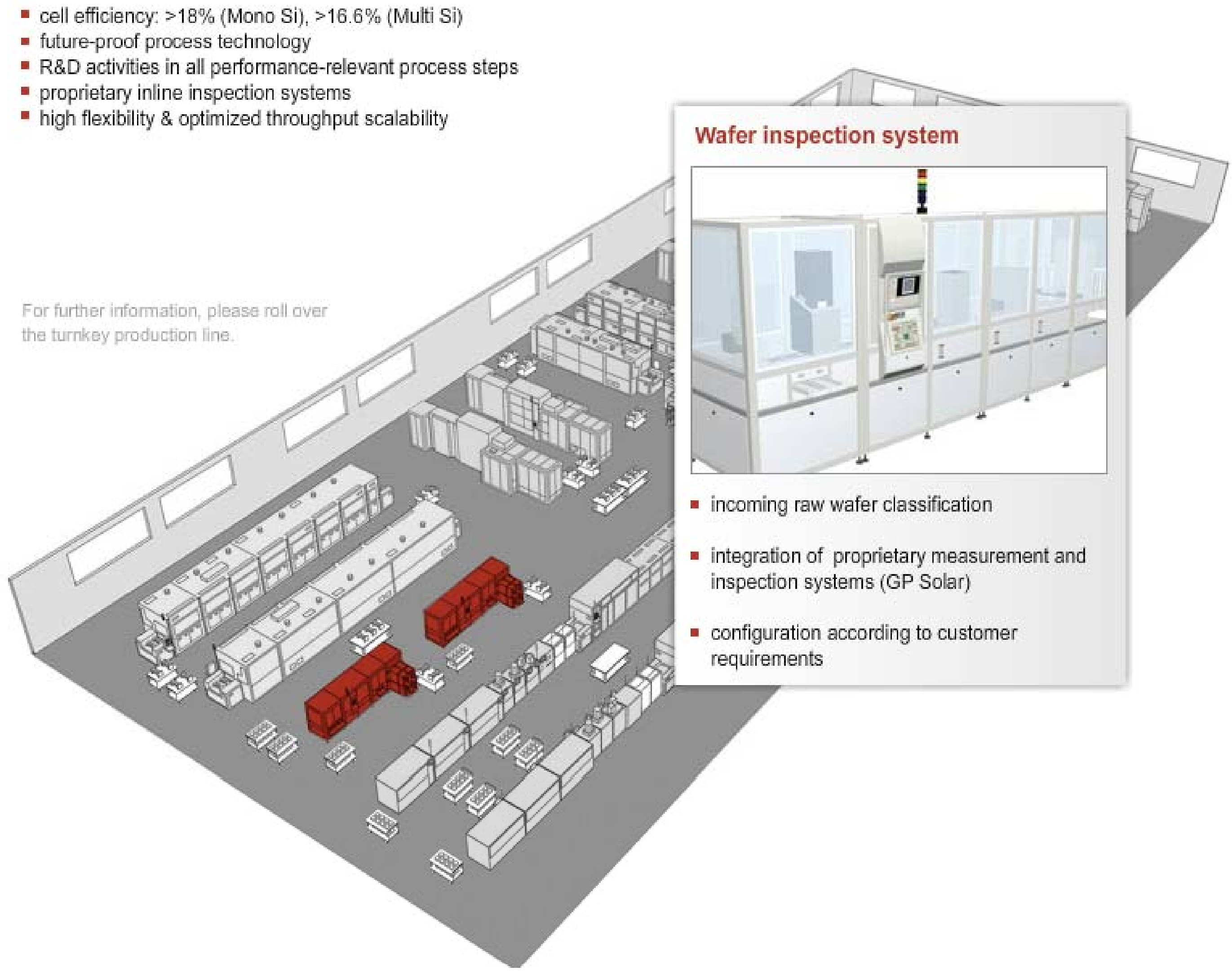


Cell Fabrication Process: State-of-the-Art

- Saw damage/texturization etch
- Selective emitter diffusion
- PSG etch
- Nitride ARC
- Metallization
- Firing
- Edge isolation
- Test and Sort



Turn-Key Solar Cell Line



http://www.centrotherm.de/fileadmin/html/flexLine/FlexLine_EN.html

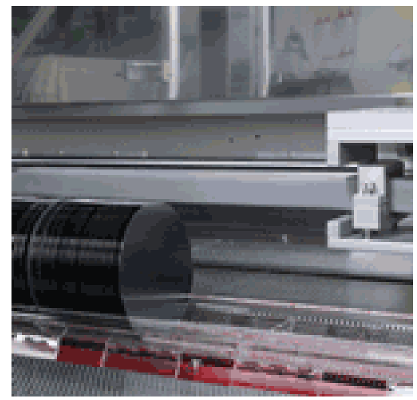
In-Line Etch Tools

For the visuals from this slide, please see the lecture video or follow the link below.

http://www.rena.com/index.php?id=40&L=1

Emitter Diffusion ($POCl_3$) Tools

Automated, high-volume batch processing for diffusion ($POCl_3$).



http://www.centrotherm.de/en/technologies-solutions/photovoltaics/production-equipment/diffusion-furnace/

Silicon Nitride ARC

Silicon nitride antireflection coatings (ARC)
Additional benefit: Hydrogen passivation

For the visuals from this slide, please see the lecture video or follow the link below.

http://www.centrotherm.de/ http://www.roth-rau.de/index_engl.html

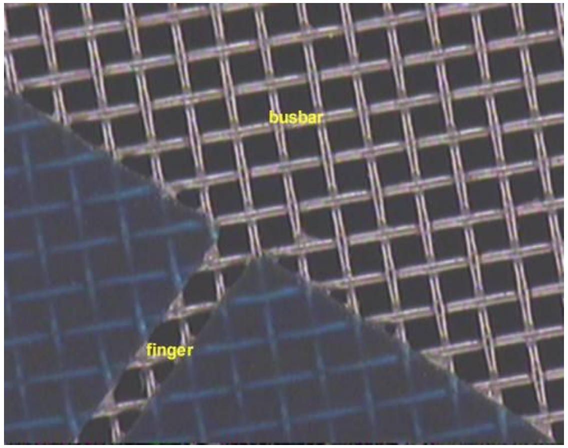
Screen Printing

Screen printing for metallization developed, proven.

> Amazingly, it works, although front metal only contacts a tiny percentage of the emitter!

> Avoids galvanization, increases throughput.

For the additional visuals from this slide, please see the lecture video or follow the links below.



Screen printing a shirt.
http://www.sportop.com/screen-printing-services.cfm

Solar cell screen
http://pvcdrom.pveducation.org/MANUFACT/Images/SCN_MESH.JPG

Screen printing a solar cell.
http://www.sportop.com/screen-printing-services.cfm

Close-up of screen printed metallization finger
http://www.polykomp.com/images/ESM300Unplated.gif

Test and Sort

For the visuals from this slide, please see the lecture video or follow the links below.

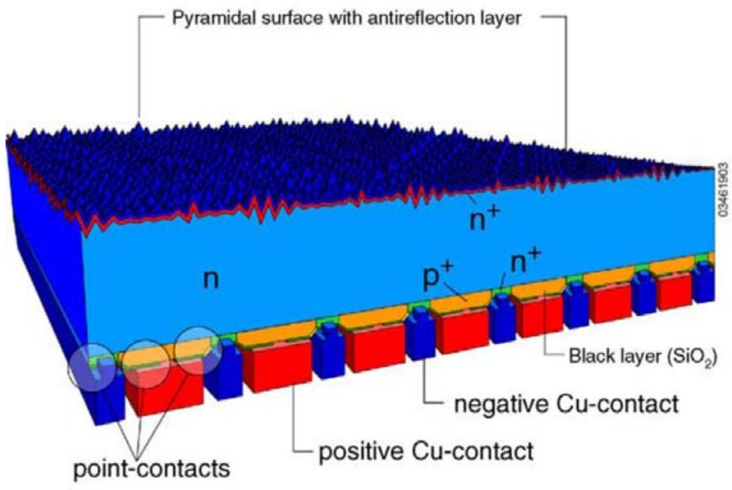
http://www.spirecorp.com/images/spire_solar/products/interconnect_solar_cells/SPI-ASSEMBLER_5000_animated.gif

http://www.spirecorp.com/spire-solar/

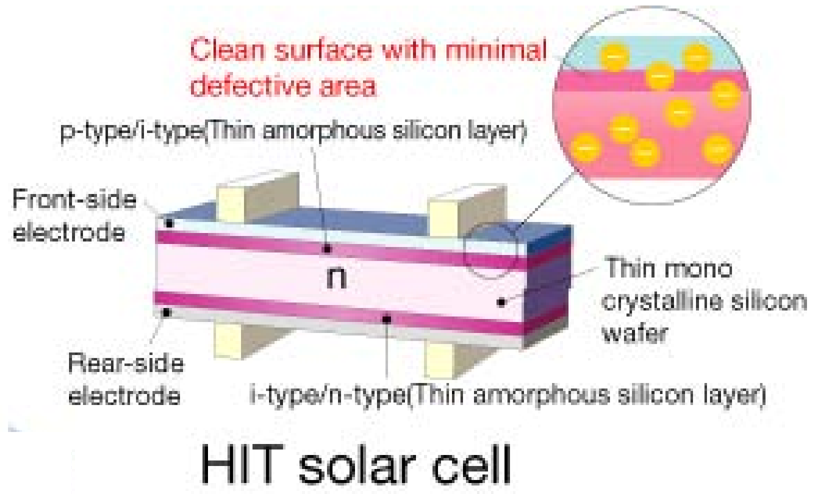
http://www.spirecorp.com/spire-solar/downloads/datasheets-april12009/Spi-Cell%20Sorter%20Rev%20B%2011-08.pdf

Very High Efficiency c-Si Architectures

- Examples:
  - SunPower Interdigitated Back Contact (~23.5%)
  - Sanyo HIT Cell (~23%)
- Characteristic Features: Both use n-type silicon

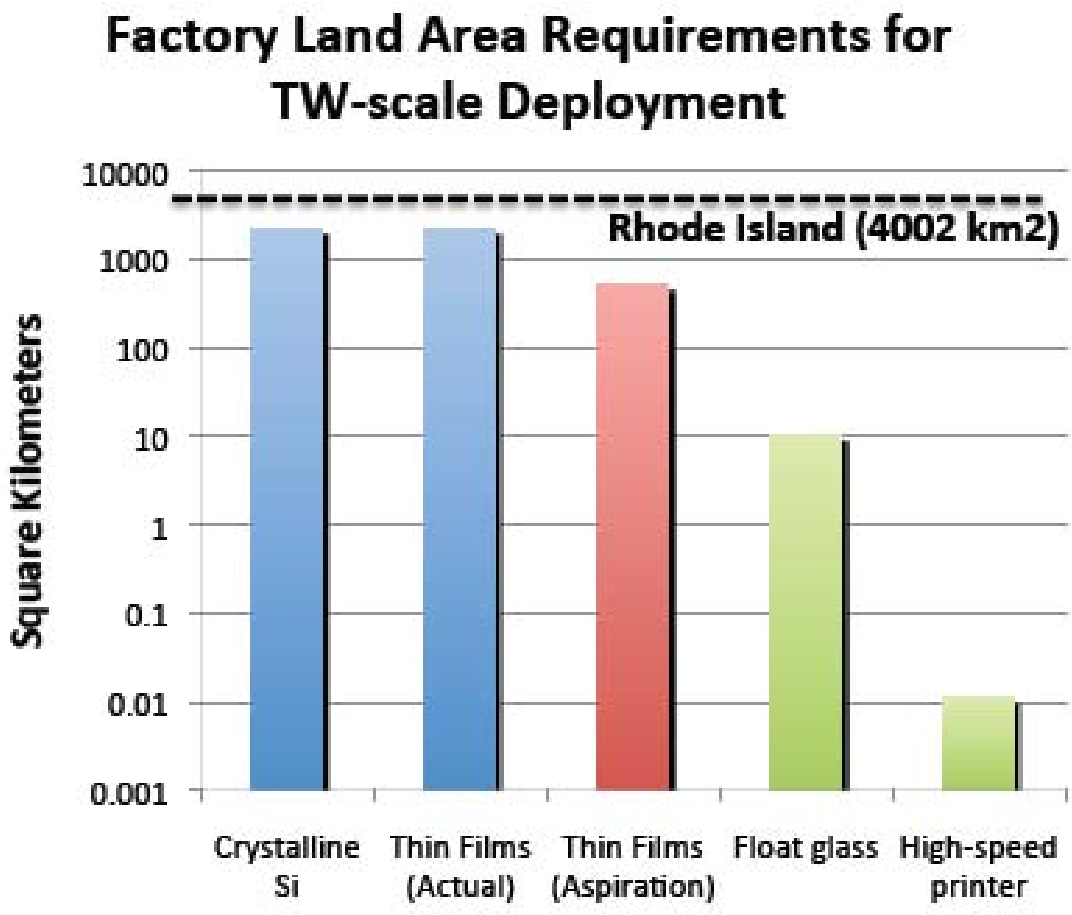


http://www.sunpowercorp.com



http://www.sanyo.co.jp/clean/solar/hit_e/hit.html

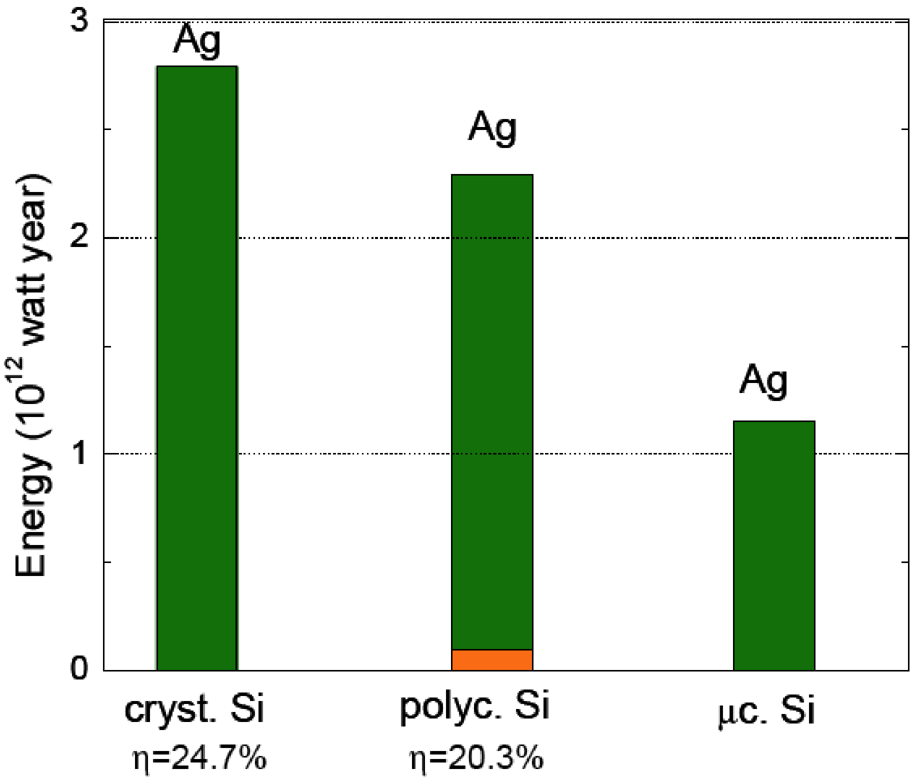
Manufacturing Barrier to Scale



Materials Availability

Plenty of (oxidized) silicon in the Earth's crust, but…

Not enough silver! New solar cell contact materials needed.

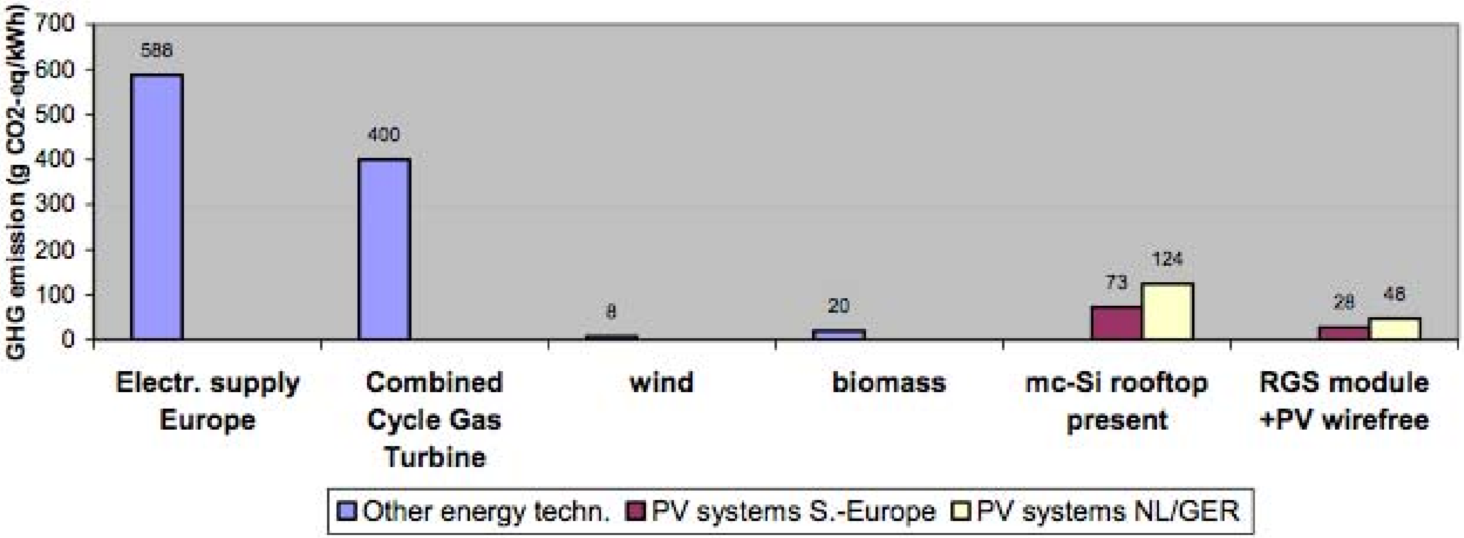


Source: Feltrin, A., and A. Freundlich. "Material Considerations for Terawatt. Level Deployment of Photovoltaics." *Renewable Energy* 33 (2008): 180-5. Courtesy of Alex Freundlich. Used with permission.

Alex Freundlich: http://www.rio6.com/proceedings/RIO6_181106_MA_1730_Freundlich.pdf

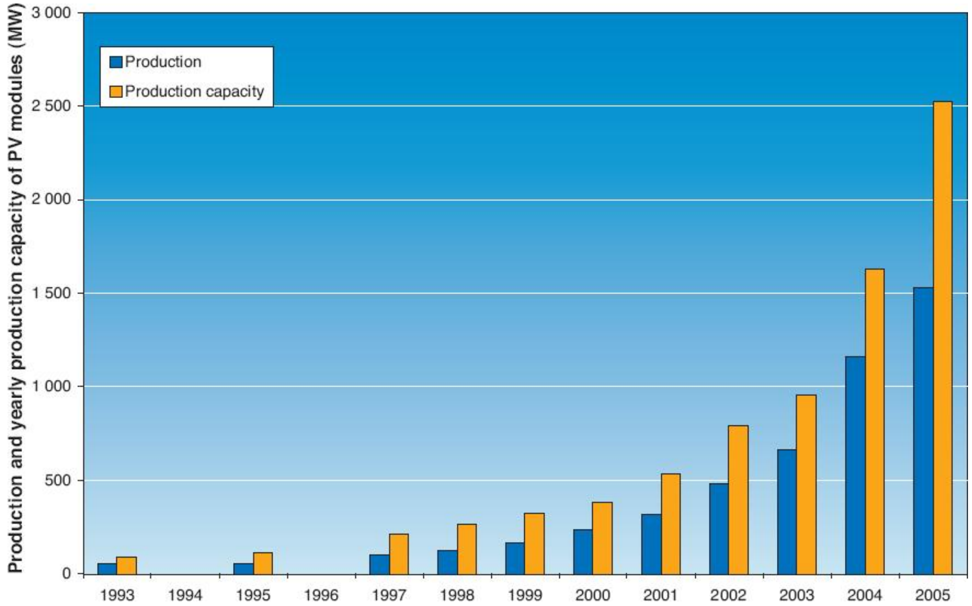
Environmental Impacts

- Links to sources concerning health, safety, and environmental impacts of PV:
  - http://www.pv.bnl.gov/
  - http://lea.web.psi.ch/
  - http://www.ecn.nl/
  - http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/setplan.cfm



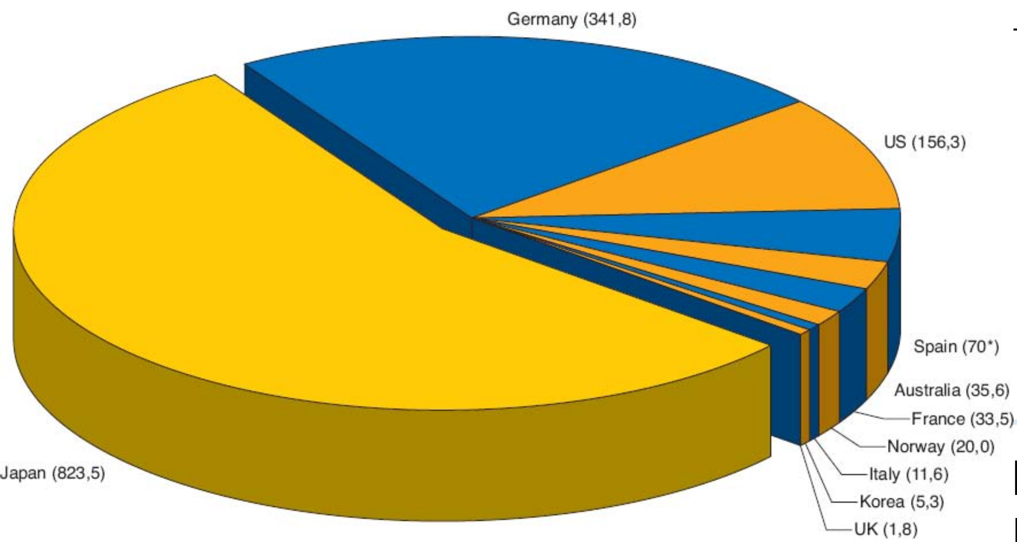
http://www.ecn.nl/docs/library/report/2004/rx04060.pdf

Declining US Market Share



- Sustained 25-40% industry growth rates.
- PV now a $10+ bi industry.

IEA-PVPS, Report IEA-PVPS T1-15:2006



US Market Share:
1980: 75%
1990: 33%
2000: 26%
2005: 10%

PV News, PV Insider's Report, Feb. 2001
IEA-PVPS: Report IEA-PVPS T1-15:2006

Images courtesy IEA Photovoltaic Power Systems Programme. Source: Trends Report 2005, http://www.iea-pvps.org/index.php?id=95&eID=dam_frontend_push&docID=156

Silicon-Based Solar Cells Tutorial

- Why Silicon?
- Current Manufacturing Methods
  – Overview: Market Shares
  – Feedstock Refining
  – Wafer Fabrication
  – Cell Manufacturing
  – Module Manufacturing
- Next-Gen Silicon Technologies

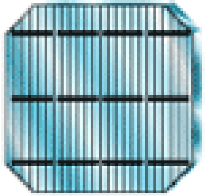
Si-based PV Production: From Sand to Systems

Module Fab

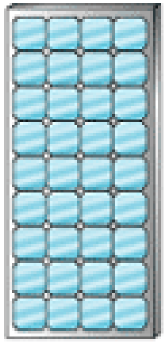
Raw Materials

Si Feedstock

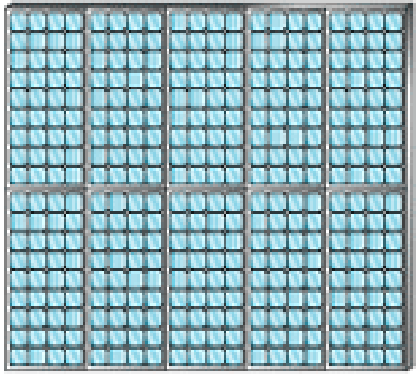
Wafer



Cell



Module



System

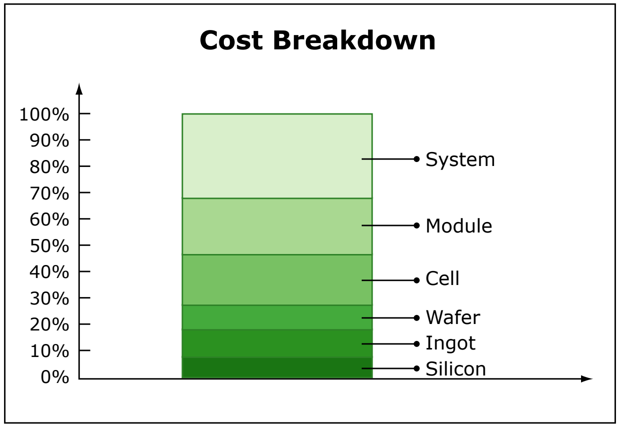


Image by MIT OpenCourseWare. After H. Aulich, PV Crystalox Solar.

Module Production Line

For related visuals, please see the lecture 11 video.

Tabbing, Stringing, and Layup

For related visuals, please see the lecture 11 video.

Module Fabrication

Laminator

Trim and frame

For related visuals, please see the lecture 11 video.

Finish (J-box)

Barriers to Scale

Fast processing of thin (~100 μm) wafers with high yield!

For related visuals, please see the lecture 11 video.

Suction cups.

http://www.spirecorp.com/images/spire_solar/products/vac_660_pict_4.jpg

Bernoulli grippers.

http://www.astec-halbleitertechnologie.de/docs/cc/download/PB_WTS-SC.pdf?PHPSESSID=83f7709a94d900a00e3dd1da5e056311

Directional Solidification of mc-Si

a.k.a. Directional Solidification System (DSS), Casting, Bridgman Process.

Ingots are initially cut into rectangular blocks called “bricks,” then wire-sawed into wafers.

Please see lecture video for related furnace and brick-cutting images.