2.626 Fundamentals of Photovoltaics
Fall 2008

Wafer Silicon-Based PV

Lecture 9 – 2.626

Tonio Buonassisi

General Announcements

- Quiz #1
- Class Projects

Outline of Today's Lecture

- Illuminated IV Curves: Efficiency, J_{sc}, V_{oc}
- Notes about Efficiency
- Overview of PV Technologies
- Manufacturing of Silicon-Based Solar Cells

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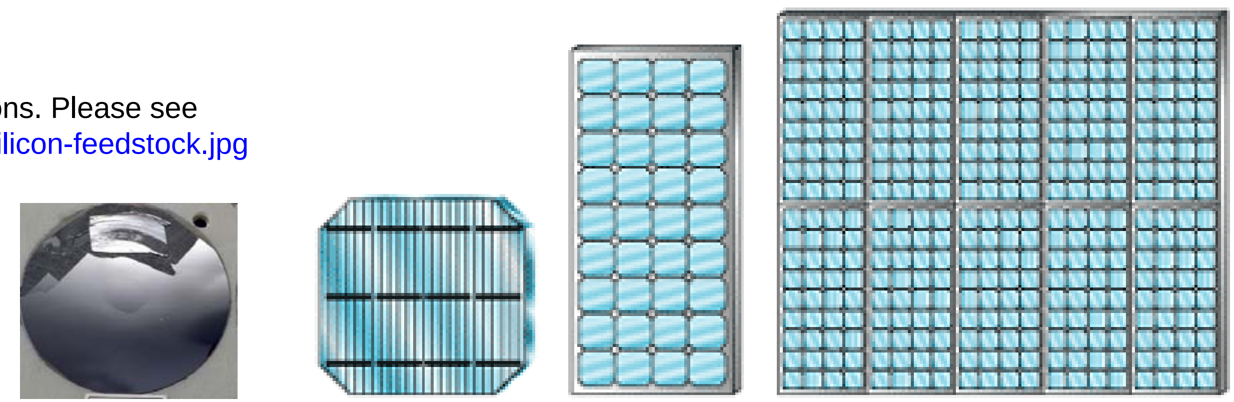
http://solarpowerindustries.com/Images/silicon-feedstock.jpg



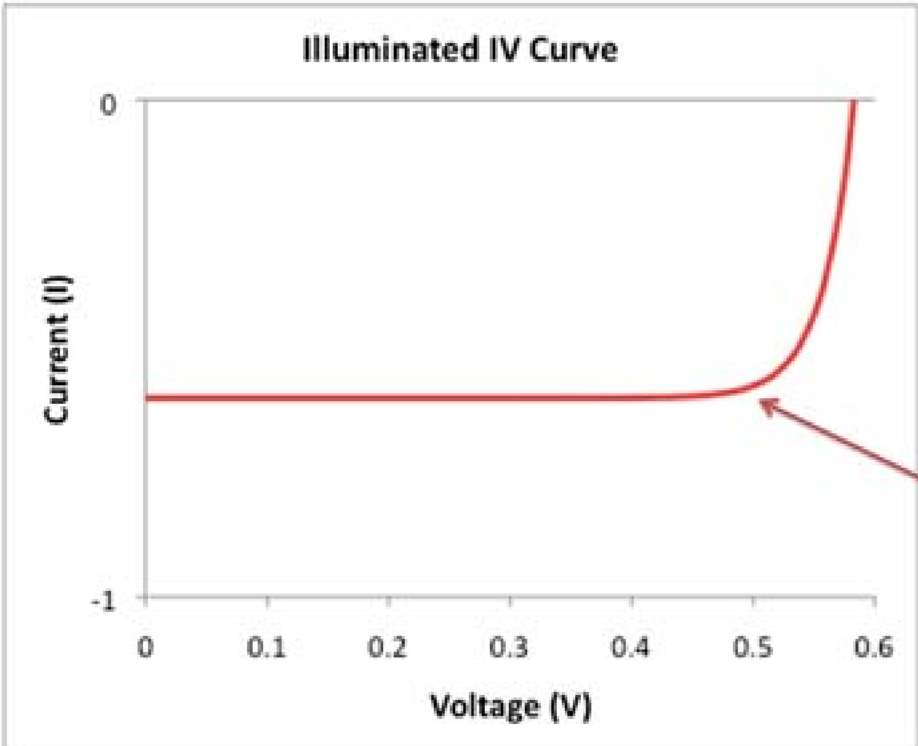
Feedstock | Wafer | Cell | Module | Array

Courtesy NASA and EERE.

Reading Assignment

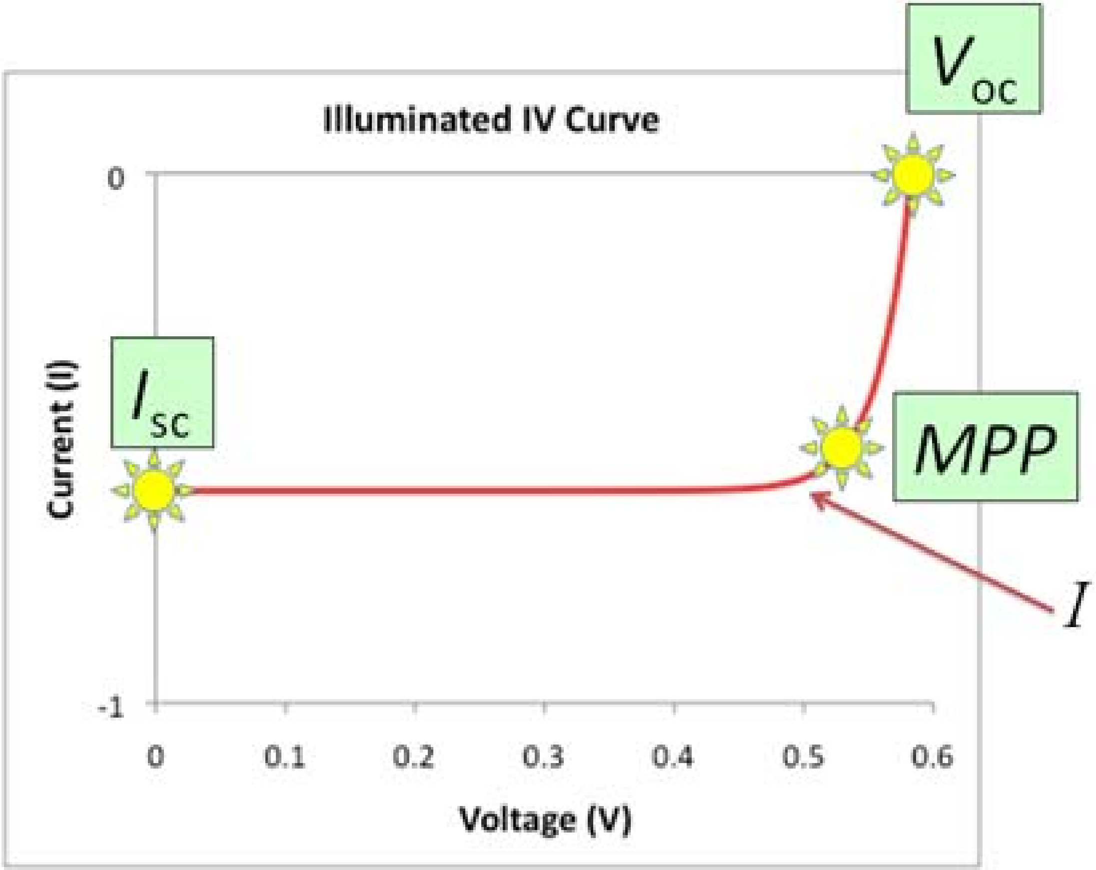
- Read: PVCDROM: Chapters 5 and 6

Efficiency Calculations



$$I = I_o\left(e^{qV/kT} - 1\right) - I_L$$

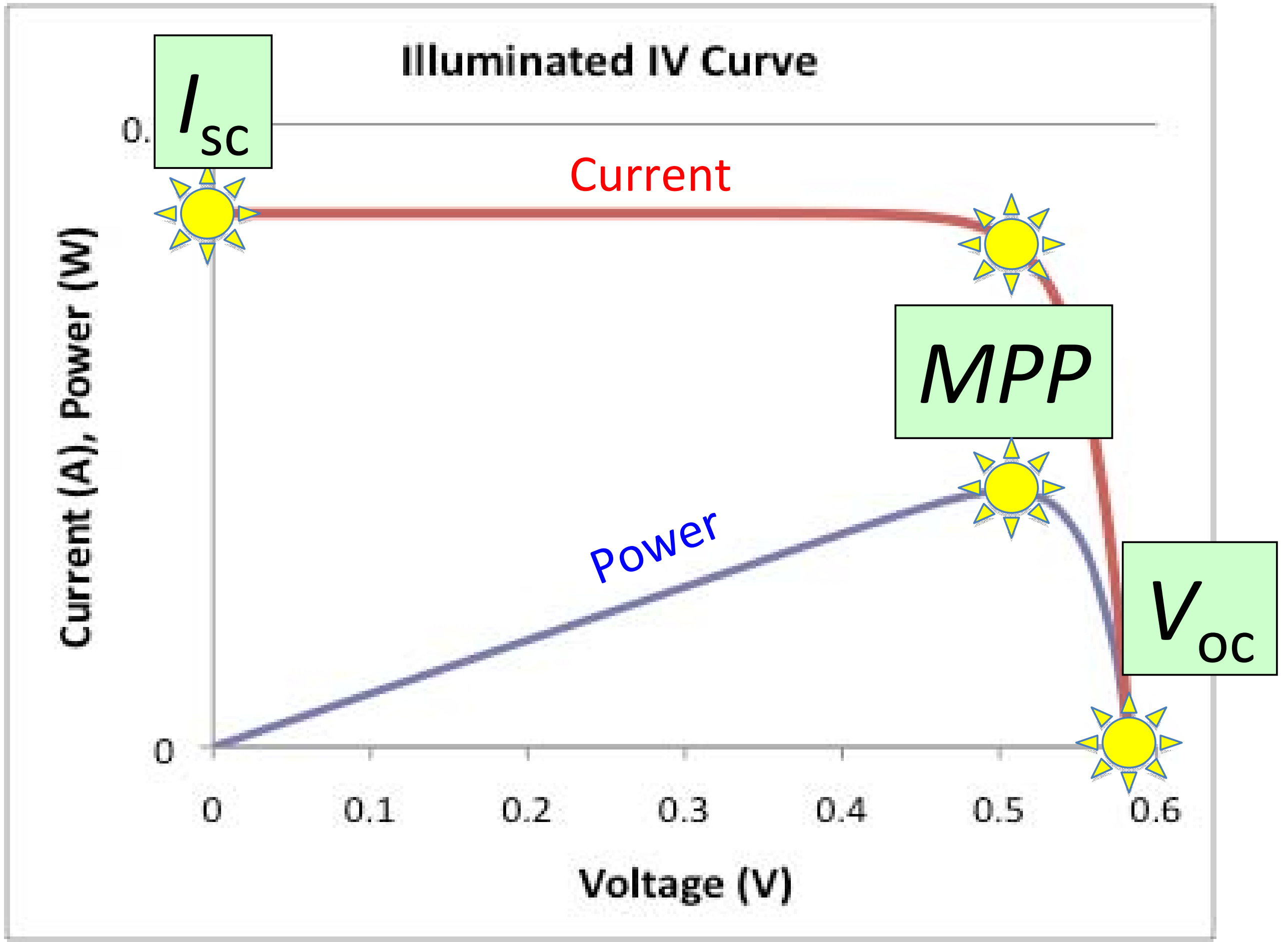
Efficiency Calculations



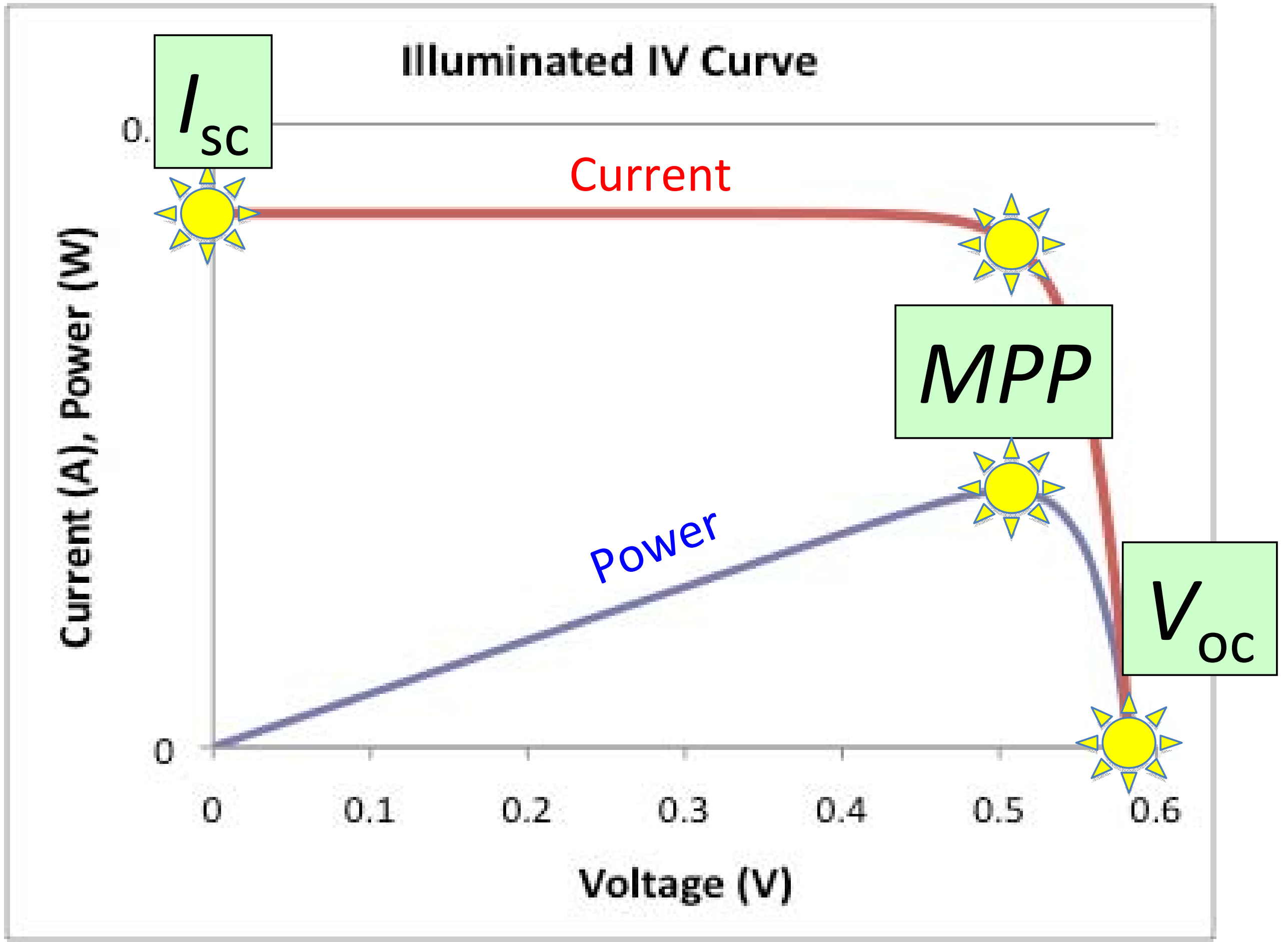
$$I = I_o\left(e^{qV/kT} - 1\right) - I_L$$

Efficiency Calculations

Industry Convention: Quadrant flipped!

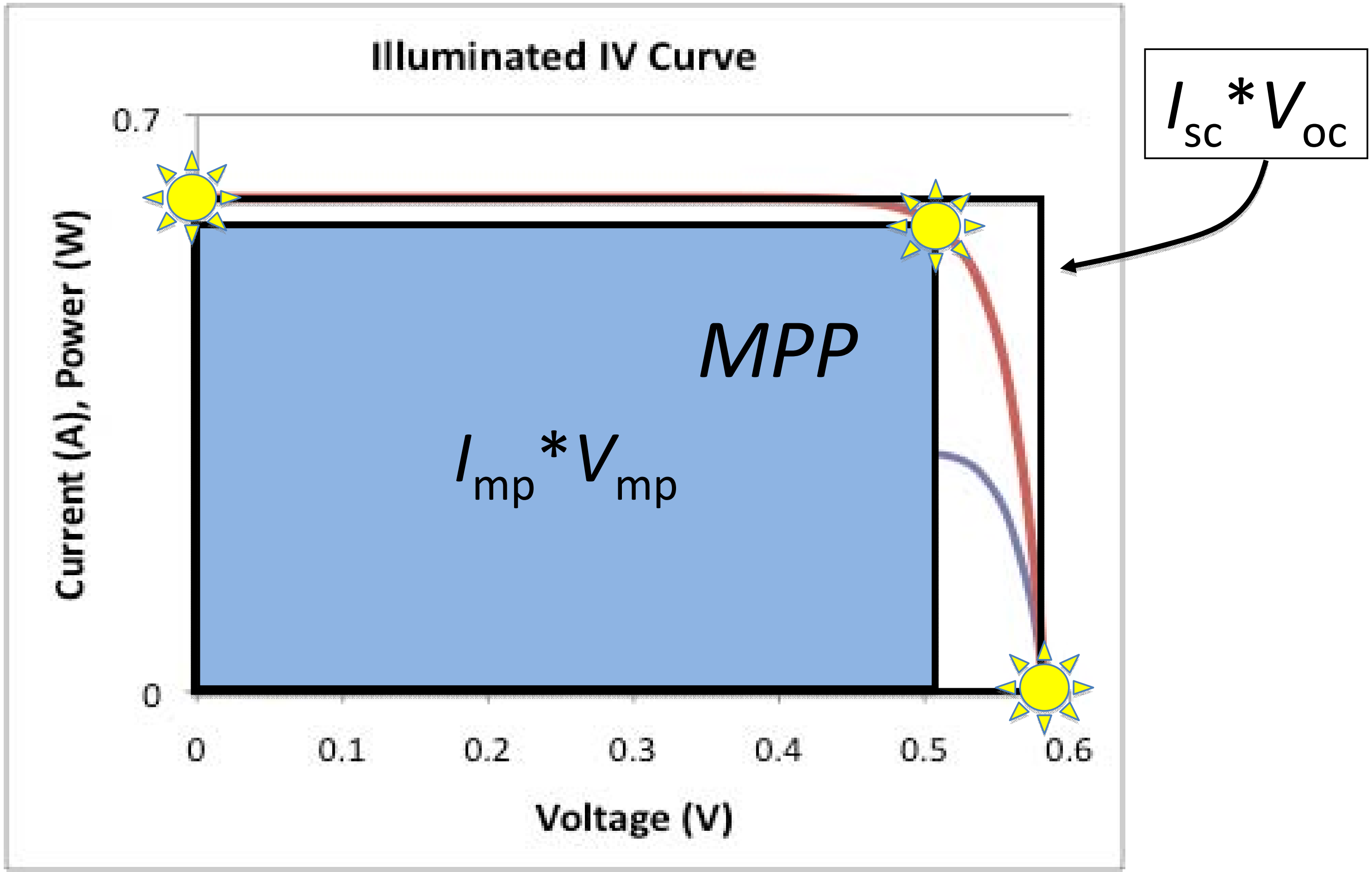


Efficiency Calculations



$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{mp} \cdot I_{mp}}{\Phi}$$

Efficiency Calculations



$$\text{Fill Factor} \equiv FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$$

Efficiency Calculations

By combining equations 1 and 2…

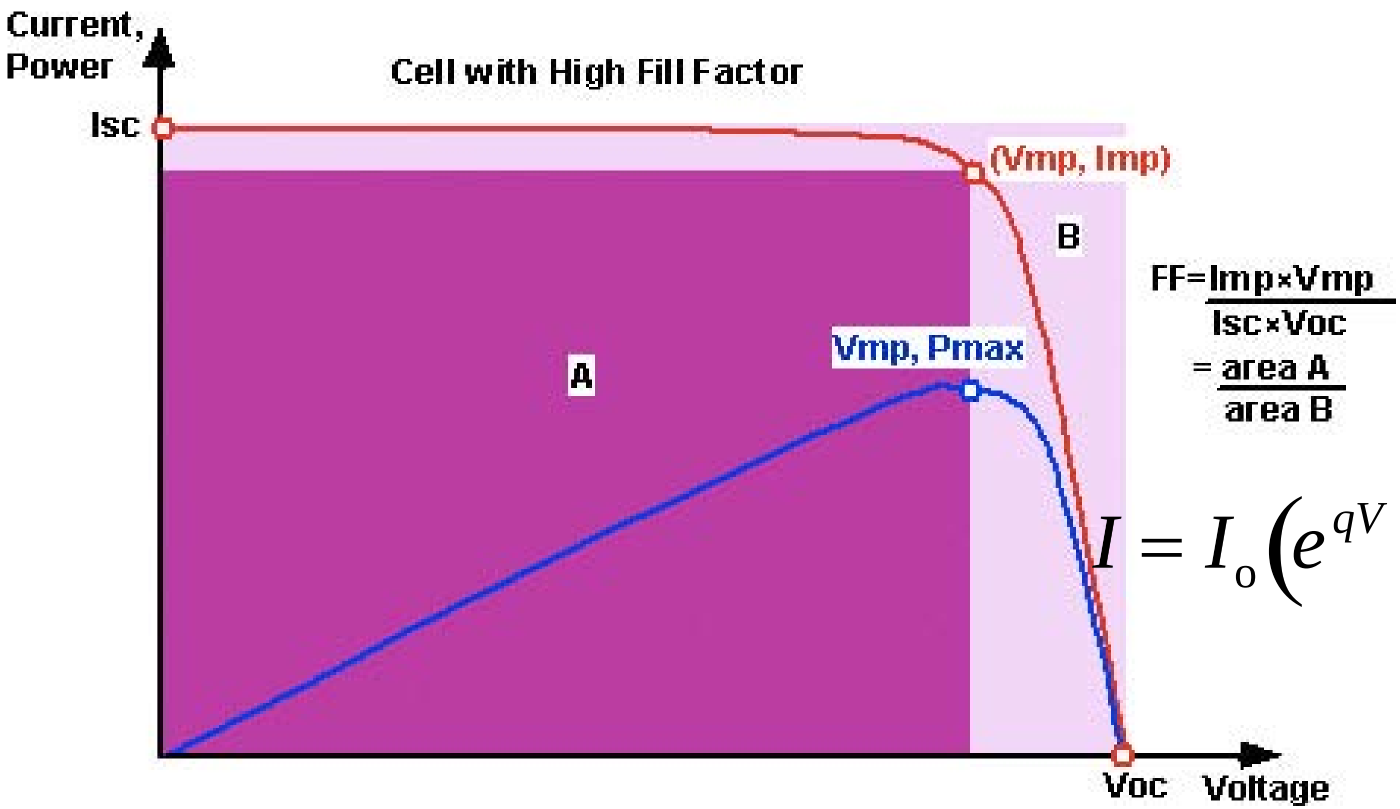
$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi}$$

$$\text{Fill Factor} \equiv FF = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{V_{\text{oc}} \cdot I_{\text{sc}}}$$

We obtain:

$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi} = \frac{FF \cdot V_{\text{oc}} \cdot I_{\text{sc}}}{\Phi}$$

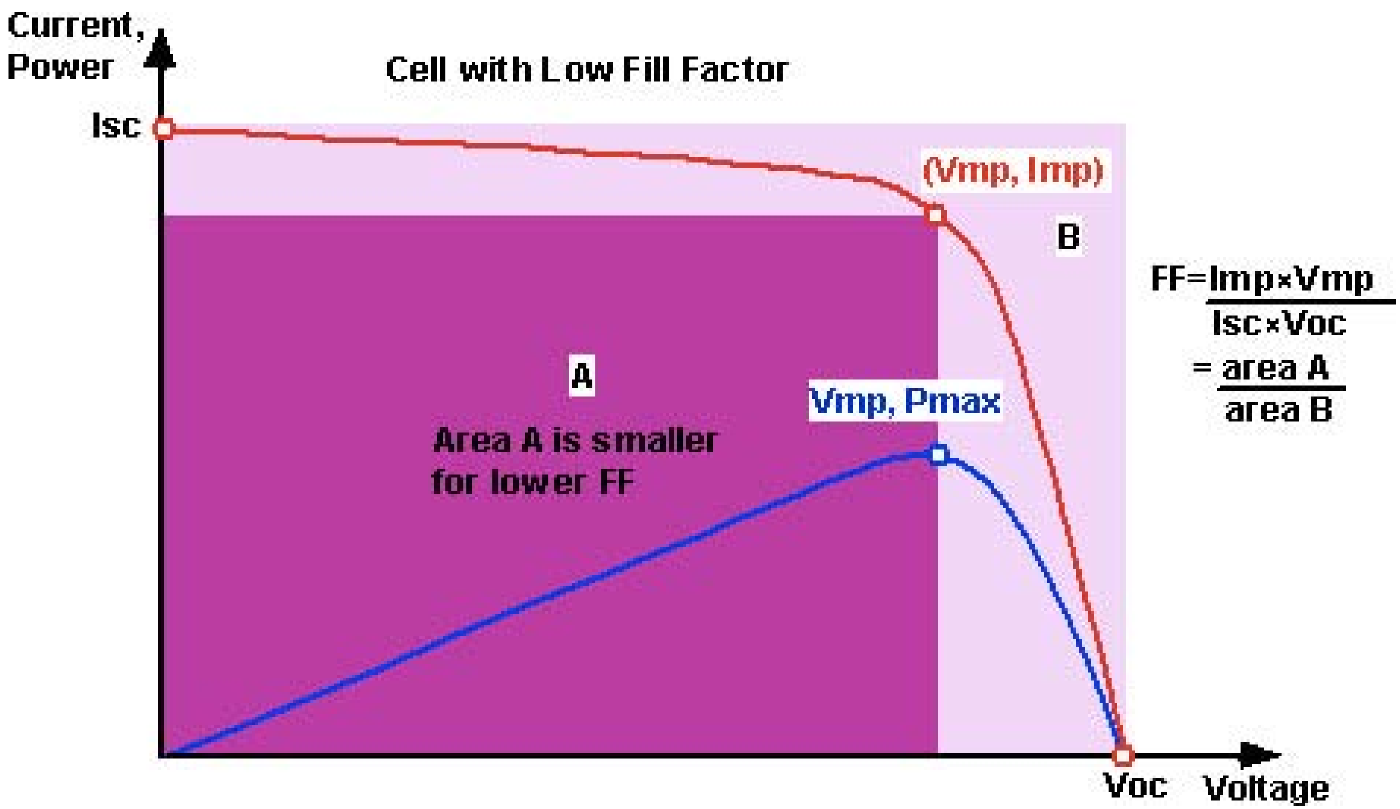
Efficiency Calculations



$$I = I_o\left(e^{qV/kT} - 1\right) - I_L$$

This is a higher-efficiency device compared to… [*next slide*]

Efficiency Calculations



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

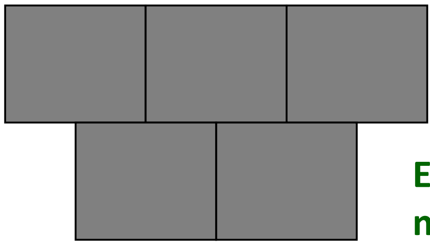
This is a lower-efficiency device, compared to the previous slide.

Efficiency of a solar cell is an important parameter

$$\eta = \frac{\text{generated electrical power}}{\text{incident light power}}$$

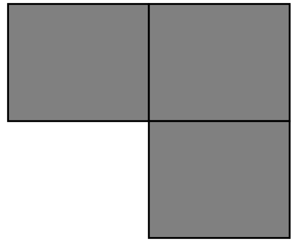
100% efficiency
(impossible to achieve)

20% efficiency
(monocrystalline
silicon solar cells)



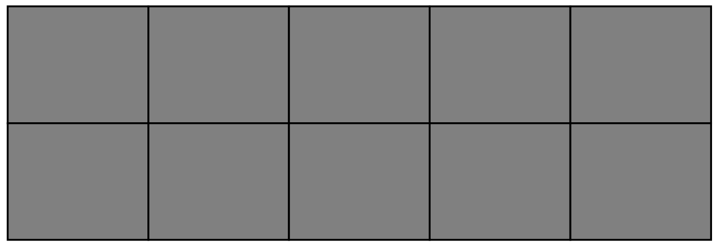
Expensive
material

33% efficiency
(space-grade solar cells)



Very
Expensive
material

10% efficiency
(amorphous
silicon solar cells)



Relatively Inexpensive material

A Note about "Efficiency"

LETTERS

Solution-processed PbS quan… infrared photodetectors anc… …ics

What does this *really* mean?

Under –5 V bias and illumination from a 975 nm laser, our detectors show an internal quantum efficiency of 3%, a ratio of photocurrent to dark current of 630, and a maximum responsivity of 3.1×10^{-3} A W^{-1}. The photovoltaic response under 975 nm excitation results in a maximum open-circuit voltage of 0.36 V, short-circuit current of 350 nA, and short-circuit internal quantum efficiency of 0.006%.

Technical Terms:

- Solar Conversion Efficiency
- External Quantum Efficiency
- Internal Quantum Efficiency

Solar Conversion Efficiency

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{J_{mp} \cdot V_{mp}}{\Phi} = \frac{FF \cdot J_{sc} \cdot V_{oc}}{\Phi}$$

Typical values are 12–20% for established technologies, <10% for most emerging technologies.

η and Φ_F: Vary with illumination intensity (e.g., 1 Sun)

External Quantum Efficiency

$$\text{EQE} = \frac{\text{Electrons Out}}{\text{Photons In}}$$

Typical peak values are 60–90%, depending on reflectivity.

EQE highly wavelength- and illumination-dependent!

Internal Quantum Efficiency

$$\text{IQE} = \frac{\text{Electrons Out}}{(\text{Photons In})\cdot(1-\text{Reflectivity})}$$

Typical peak values are 80–98%, depending on reflectivity.

EQE highly wavelength- and illumination-dependent!

When an efficiency quoted, think about:

- What "efficiency" is being measured?
- What is the nature of the light being used?
    - What spectrometer to simulate solar spectrum?
    - If monochromatic, what wavelength?
    - What intensity (photon flux)?
- What used car are they trying to sell me?

An example of honest efficiency reporting

Text removed due to copyright restrictions. Please see the Abstract of Huynh, Wendy U., Janke J. Dittmer, and A. Paul Alivisatos. “Hybrid Nanorod-Polymer Solar Cells.” *Science* 295 (March 29, 2002): 2425-2427.

W.U. Huynh, *Science* **295** (2002) 2425

Solar Cell Efficiency Tables

Table removed due to copyright restrictions. Please see Table I in Green, Martin A., et al. "Solar Cell Efficiency Tables (Version 27)." *Progress in Photovoltaics: Research and Applications* 14 (2006): 45-51.

M.A. Green, *Prog. Photovolt: Res. Appl.* **14** (2006) 45

Module Efficiency Tables

Table removed due to copyright restrictions. Please see Table II in Green, Martin A., et al. “Solar Cell Efficiency Tables (Version 27).” *Progress in Photovoltaics: Research and Applications* 14 (2006): 45-51.

M.A. Green, *Prog. Photovolt: Res. Appl*. **14** (2006) 45

Diversity of PV Devices

Photovoltaic Device Fundamentals

(1) Charge Generation: Light excites electrons, freeing them from atomic bonds and allowing them to move around the crystal.

(2) Charge Separation: An electric field engineered into the material (pn junction) sweeps out electrons.

(3) Charge Collection: Electrons deposit their energy in an external load, complete the circuit.

Advantages: There are no moving parts and no pollution created at the site of use (during solar cell production, that's another story).

Disadvantages: No output at night; lower output when weather unfavorable.

For full animation, see: http://micro.magnet.fsu.edu/primer/java/solarcell/

Technological Diversity

http://peswiki.com/images/8/86/Spheral_solar_panel_95x95.jpg

Fig. 1 in Takamoto, Tatsuya, et al. “Over 30% efficient InGaP/GaAs tandem solar cells.” *Applied Physics Letters* 70 (January 20, 1997): 381-383.

Spheral Solar

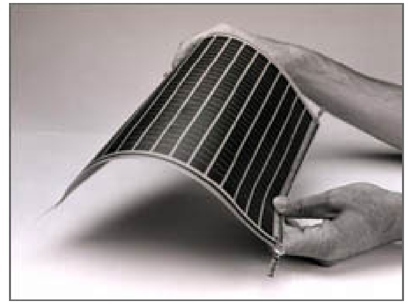
http://site.novatechgadgets.com/evtechfeat.jpg

http://www.stangl.de/typo3temp/pics/691aeb319e.jpg

Copper Indium Diselenide (CIS)

Silicon Ribbon

Heterojunction Cells



Courtesy EERE.

Amorphous Silicon

http://www.atp.nist.gov/eao/sp950-1/astropw1.jpg

http://www.iea-pvps.org/ar/ar00/images/aus03.jpg

http://www.ajeal.net/english/wp-content/uploads/solar-panel-cost.jpg

Cadmium Telluride

http://www.triplepundit.com/nanosolar.jpg

Dye-sensitized Cells

Silicon Sheet

Hybrid (nano)

Courtesy NASA.

http://commons.wikimedia.org/wiki/File:Multicrystallinewafer_0001.jpg

http://electronicdesign.com/Files/29/11527/Figure_01.jpg

http://www.livescience.com/images/0412_solar_panels_03.jpg

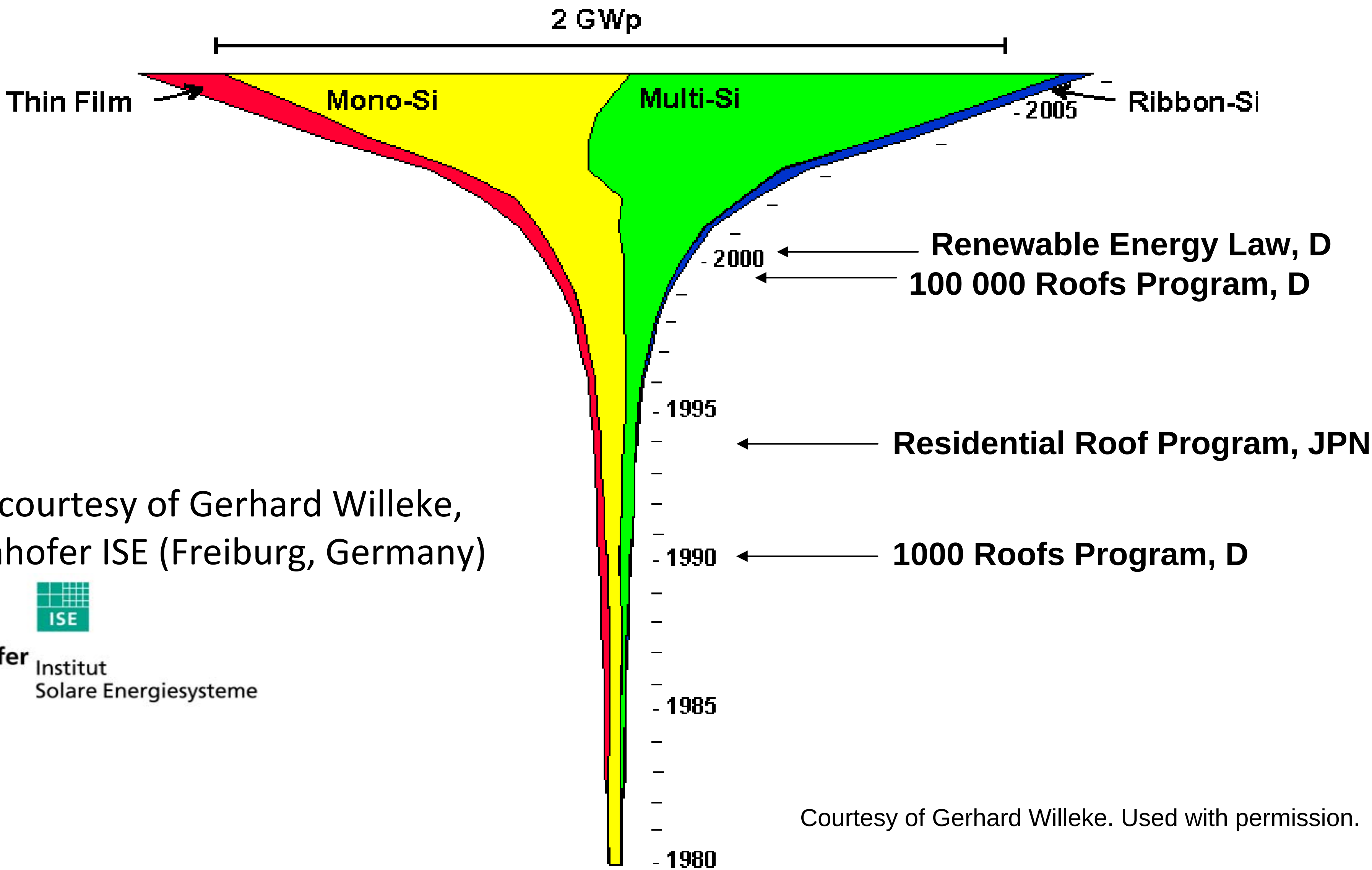
Monocrystalline Silicon

Multicrystalline Silicon

SunPower Back-contacted

Organics

Photovoltaics: State of the Art

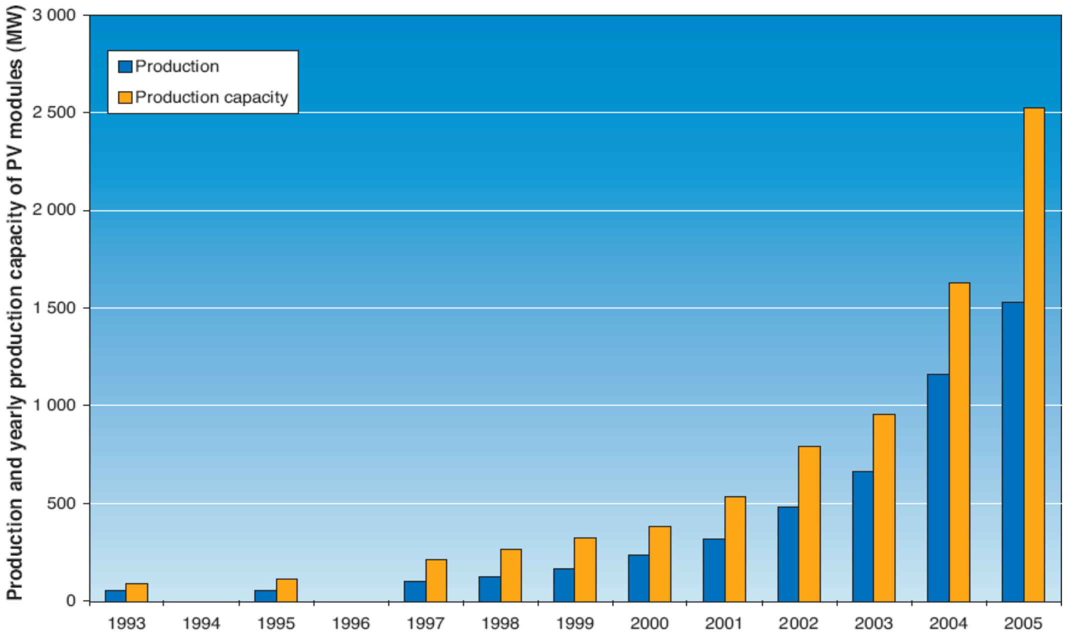


Slide courtesy of Gerhard Willeke,
Fraunhofer ISE (Freiburg, Germany)

Fraunhofer Institut Solare Energiesysteme

Silicon Photovoltaics – Wafer Substrates

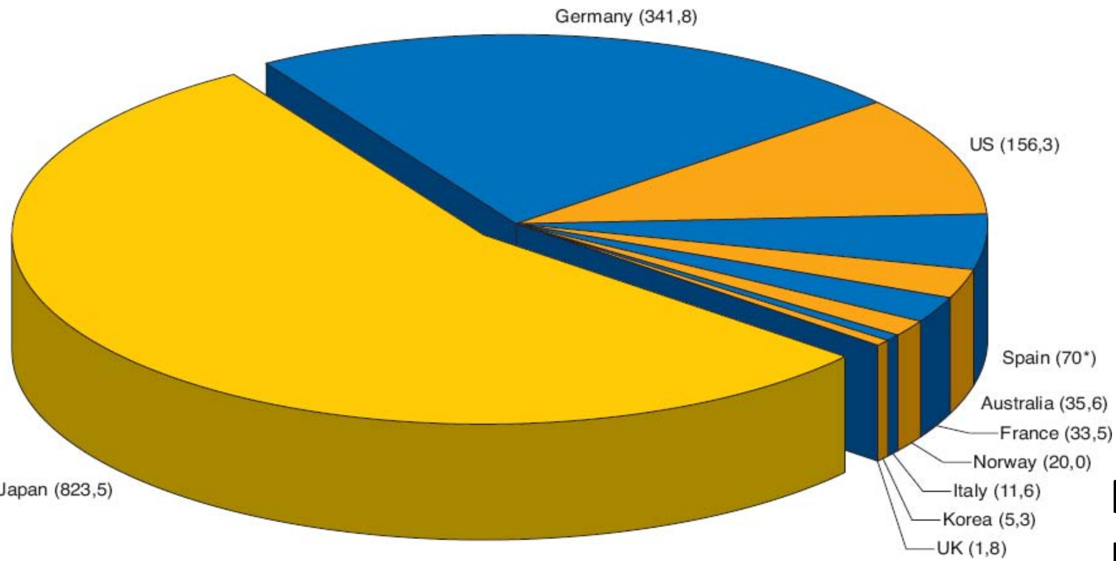
Worldwide PV Production



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

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

Images courtesy IEA Photovoltaic Power Systems Programme.



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

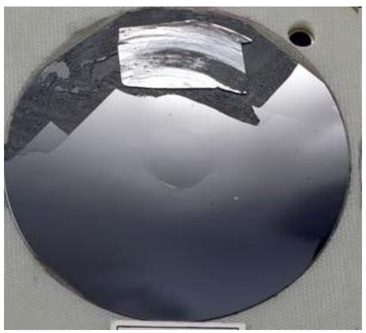
Silicon is the second most abundant element on Earth after oxygen (28% of the Earth's crust). Its most familiar forms are sand and quartzite (the latter one is more pure).

Silicon in Nature: It's <u>everywhere</u>!

http://commons.wikimedia.org/wiki/File:Third_beach_sand.jpg

Human-made <u>Mono</u>crystalline Silicon

http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/Czochralski_1.gif.



<u>Mono</u>crystalline Silicon

Human-made <u>Multi</u>crystalline Silicon

http://www.tkx.co.jp/english/solar/images/index_img_03.jpg

http://www.tkx.co.jp/english/solar/images/index_img_05.jpg

http://commons.wikimedia.org/wiki/File:Multicrystallinewafer_0001.jpg

<u>Multi</u>crystalline Silicon

Crystalline silicon growth technologies used in PV

- Single crystalline ingot growth
  (Czochralski (CZ) and float zone (FZ) technologies)

  → *Sunpower, Siemens Solar*

- Casting of multicrystalline silicon

  - Sharp, Kyocera, BP Solar, Shell Solar

- Ribbon growth of multicrystalline silicon

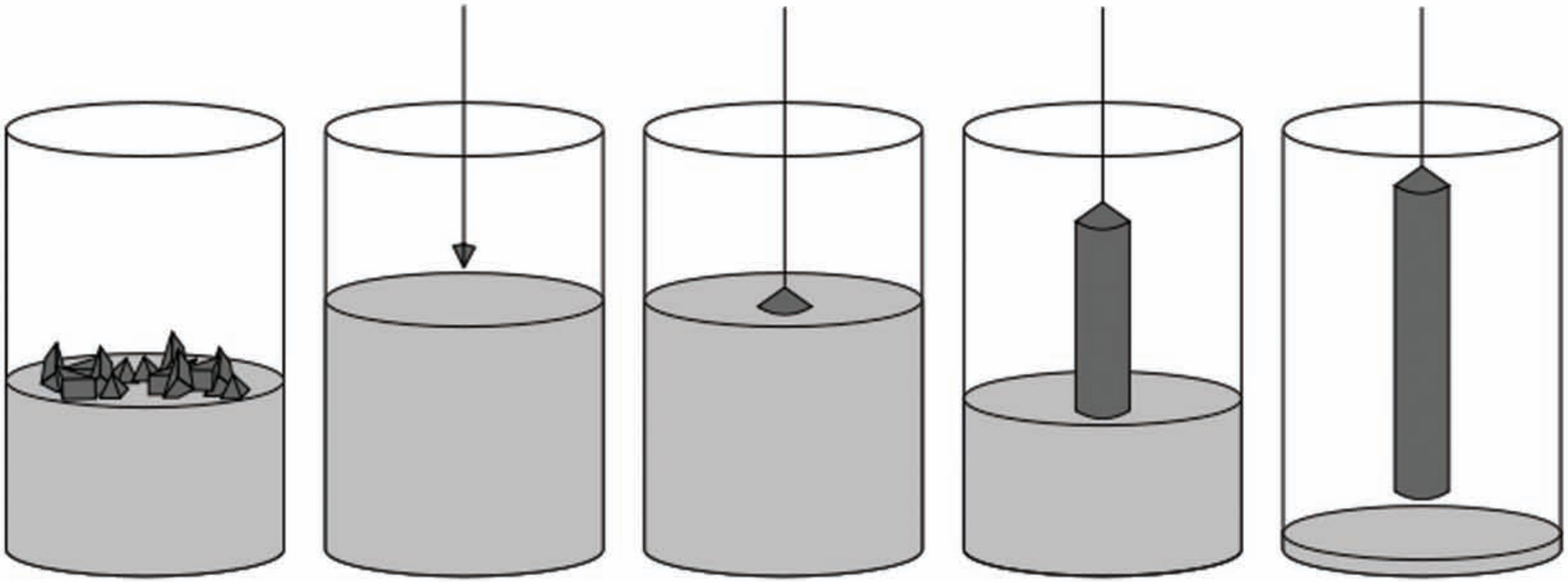
  → *Evergreen,*
  RWE Schott Solar (former ASE Americas)

- Sheet growth of multicrystalline silicon

  → *General Electric (former Astropower),*
  ECN

Czochralski (CZ) crystal growth

1916, Polish physicist Jan Czochralski



Melting of polysilicon, doping	Introduction of the seed crystal	Beginning of the crystal growth	Crystal pulling	Formed crystal with a residue of melted silicon

Si melting point 1414°C

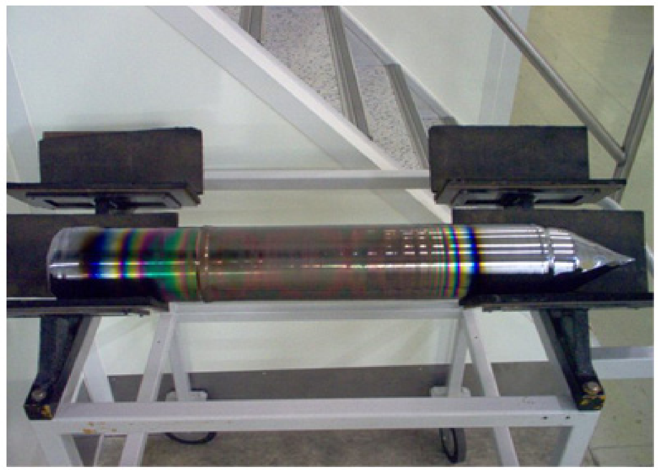
Growth rate approx. 5 cm/hour

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

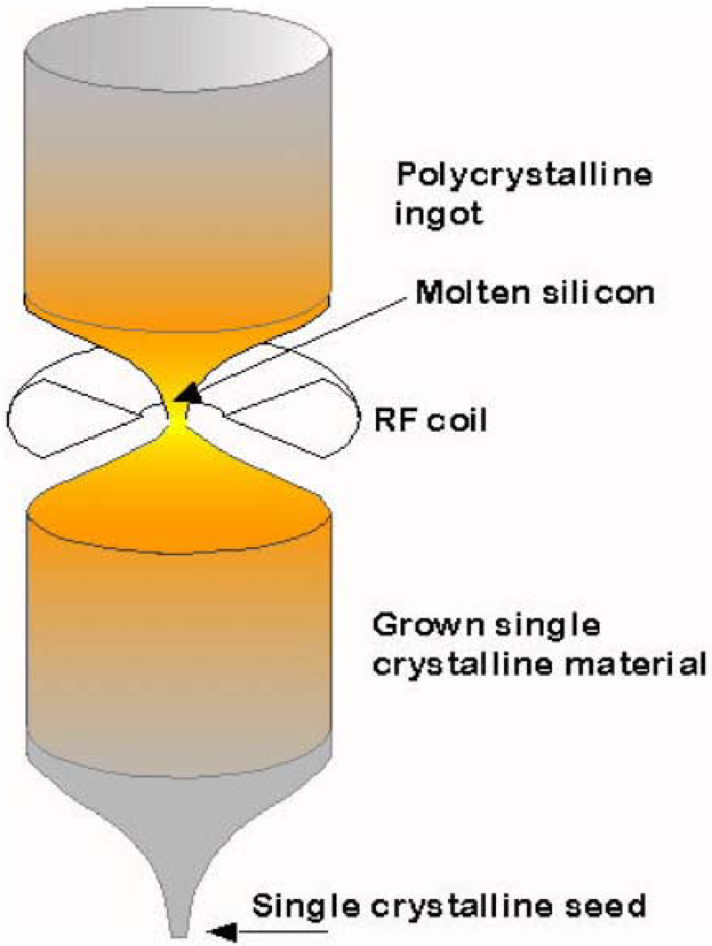
This type of silicon is the standard for integrated circuit industry. Very high quality ingots. Partial dissolution of quartz crucible introduces oxygen and carbon into the melt.

Principles of CZ growth process

Images of the Czochralski method removed due to copyright restrictions.
Please see: http://semiconductor-nano.com/images/Czochralski_2a.gif
http://semiconductor-nano.com/images/Czochralski_2c.gif
http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/Czochralski_1.gif.



Float-zone silicon growth



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

Image removed due to copyright restrictions.
Please see any photo of float zone silicon, such as
http://www2.epia.org/images/pho_profiles_A/pho_profiles_A_39.jpg.

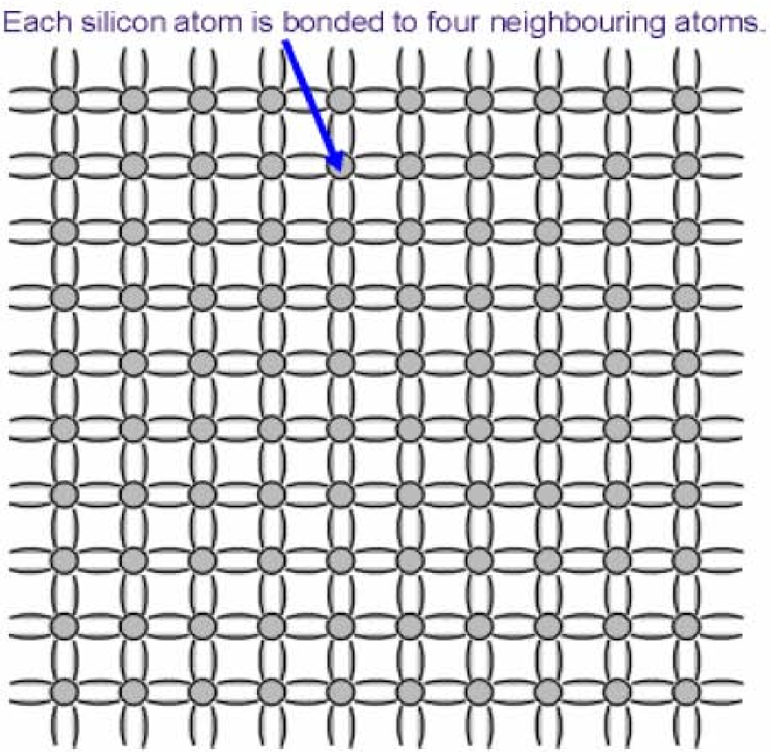
Crystal grows without contact with crucible and has the lowest possible impurity content (particularly low oxygen and carbon content). However, FZ growth appears to be more expensive than CZ growth and is used only for the most demanding applications.

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

Crystalline silicon

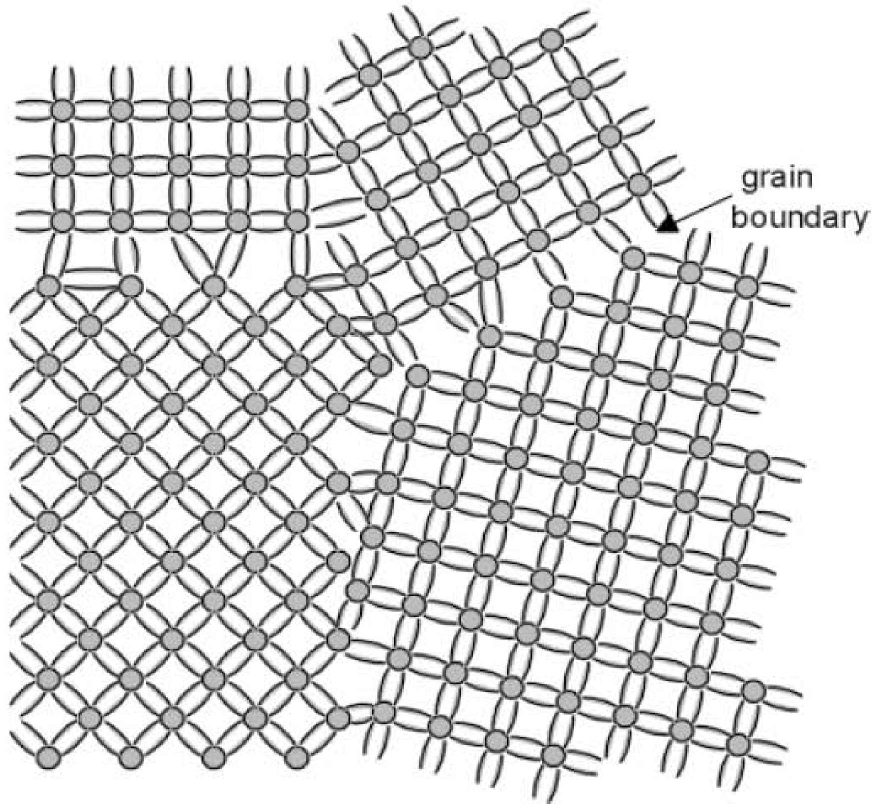
Single crystalline silicon

FZ, CZ



Multicrystalline silicon

Cast, ribbon, sheet techniques



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**.

Multicrystalline silicon is very easy to distinguish from single crystalline silicon:

grains in mc-Si are clearly visible in reflected light

Single-crystalline CZ of FZ wafer

Image removed due to copyright restrictions.
Please see any image of polycrystalline silicon, such as
http://commons.wikimedia.org/wiki/File:Multicrystallinewafer_0001.jpg.

Multicrystalline silicon wafer

Casting/directional solidification of mc-silicon

→ *Mainstream multicrystalline silicon technology*

Image removed due to copyright restrictions.
Please see http://siliconsultant.com/images/DScasting.gif.

Silicon can be solidified either in a separate crucible after it is poured from a melting crucible, or can be melted and directionally solidified in the same crucible. Crucibles are usually made of quartz or graphite, often with Si_3N_4 coating.

240 kg ingots with cross-section of 69x69 cm are grown in total cycle times of 56 hours.

Drawing from www.siliconsultant.com, Ted Ciszek

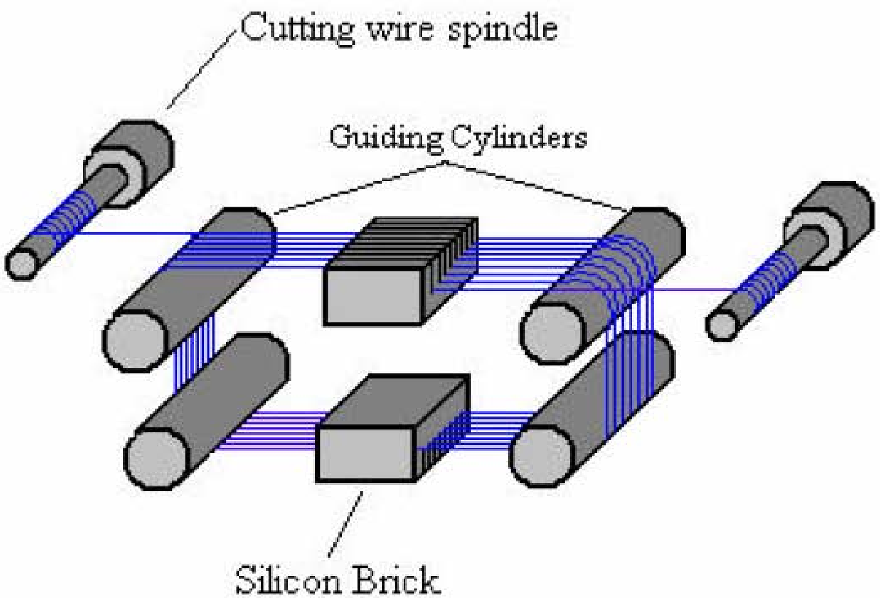
Casting of multicrystalline silicon

Images removed due to copyright restrictions.
Please see any photos of multicrystalline silicon ingots and blocks, such as
http://www.tkx.co.jp/english/solar/images/index_img_03.jpg
http://www.tkx.co.jp/english/solar/images/index_img_05.jpg.

Ingots are initially cut into rectangular blocks, and then sliced into wafers. Ingots can weigh up to 200-250 kg. The major part of mc-Si used in PV is grown by casting.

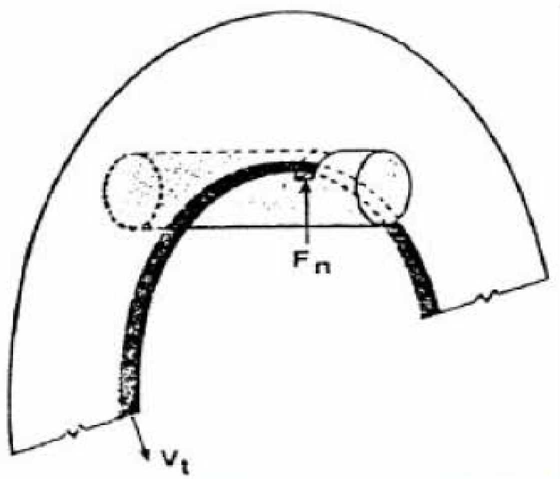
Wafering (cutting ingots into wafers)

Possible configuration of a wire saw



Abrasive wire length may be up to several km.

Inner diameter slicing



Kerf loss during sawing is typically 30-40% of silicon

Ribbon growth (A)

EFG (Edge-Defined, Film-Fed Growth) – RWE Schott Solar

Image removed due to copyright restrictions.

Please see Fig. 2 in Bell, R. O., and J. P. Kalejs. "Growth of Silicon Sheets for Photovoltaic Applications." *Journal of Materials Research* 13 (October 1998): 2732-2739.

Growth rate: 1-3 cm/min

No sawing required!

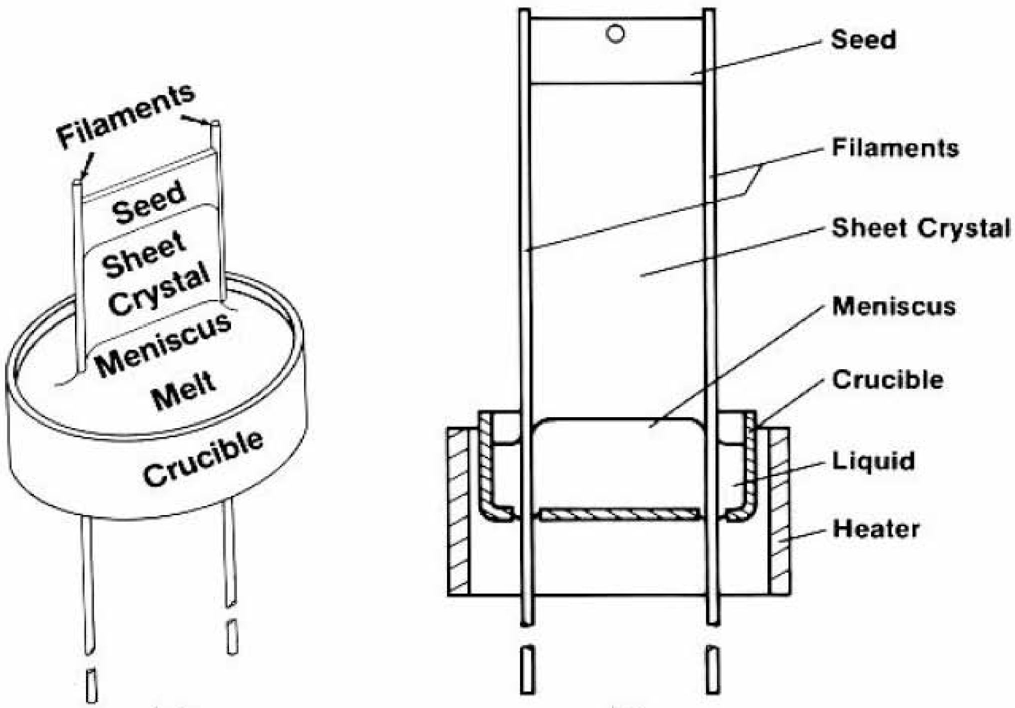
Ribbon growth (B)

String ribbon growth technique - Evergreen Solar

E. Sachs, *J. Cryst. Growth* **82** (1987) 117

Similar technique:
T.F.Ciszek and J.L.Hurd, 1980

Edge-supported pulling



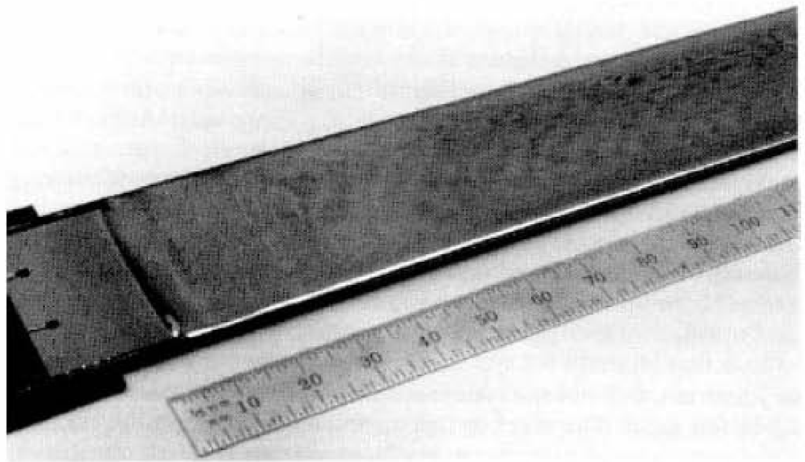
Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

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

Growth rate: 1-3 cm/min

Image removed due to copyright restrictions.
Please see http://siliconsultant.com/images/Espphoto.jpg.

Fig. 5. Hot-zone region for growth of ESP ribbons.



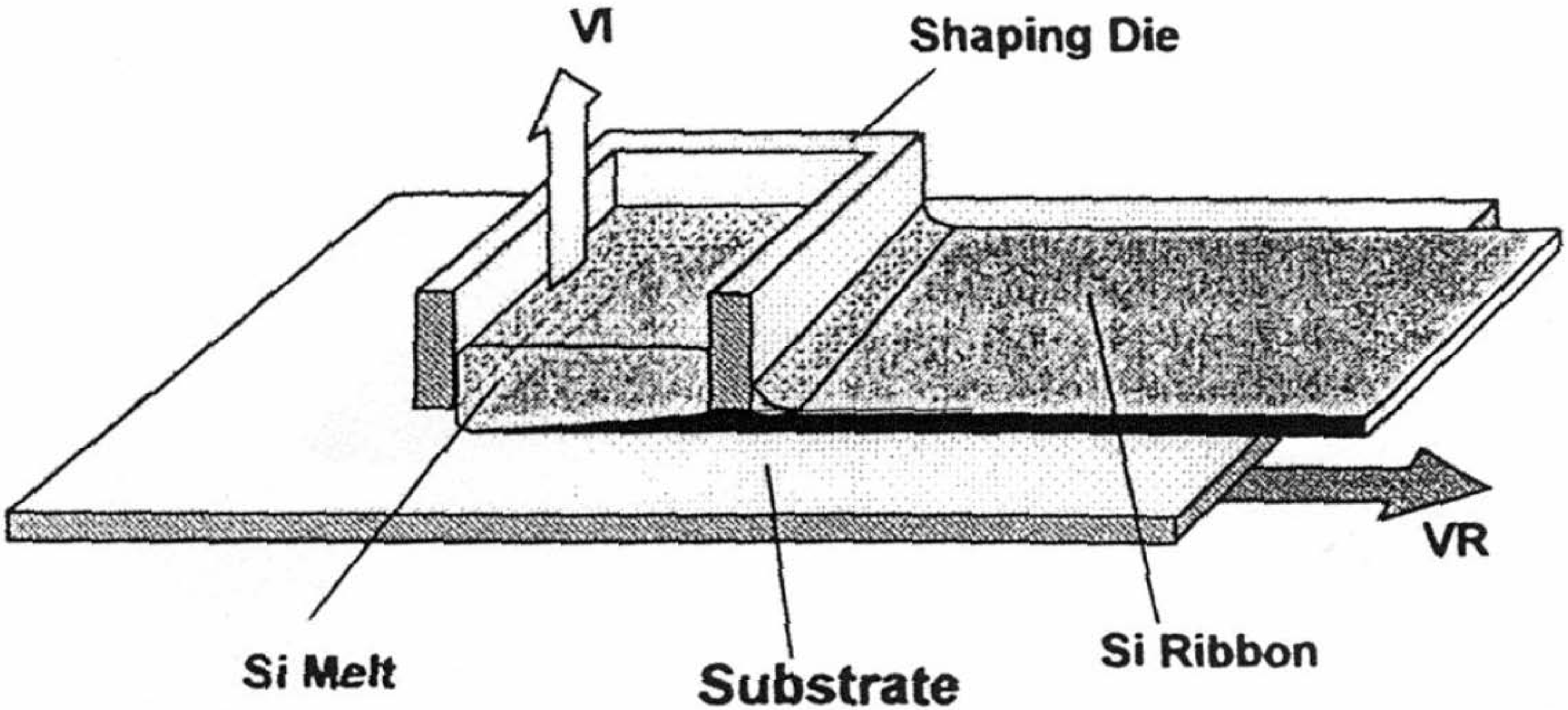
g. 6. Silicon sheet grown by edge-supported pulling using rigid graphite filaments.

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

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

Sheet Growth (A)

RGS (Ribbon Grown on Substrate) – ENC

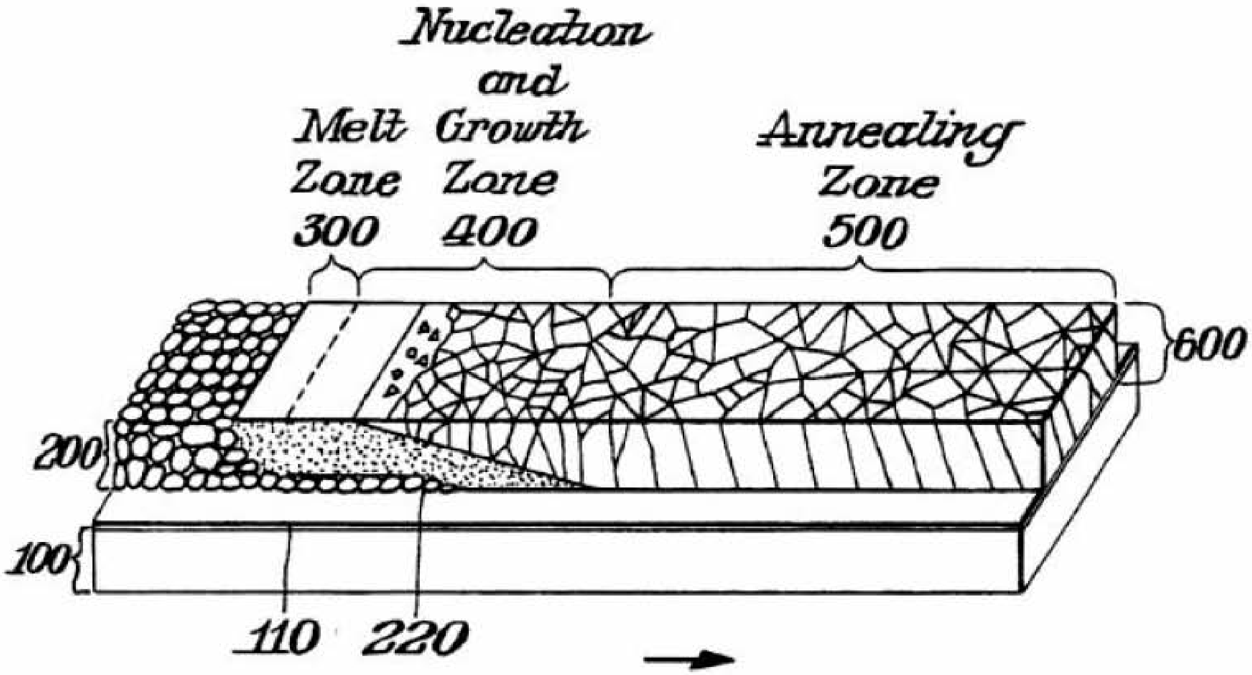


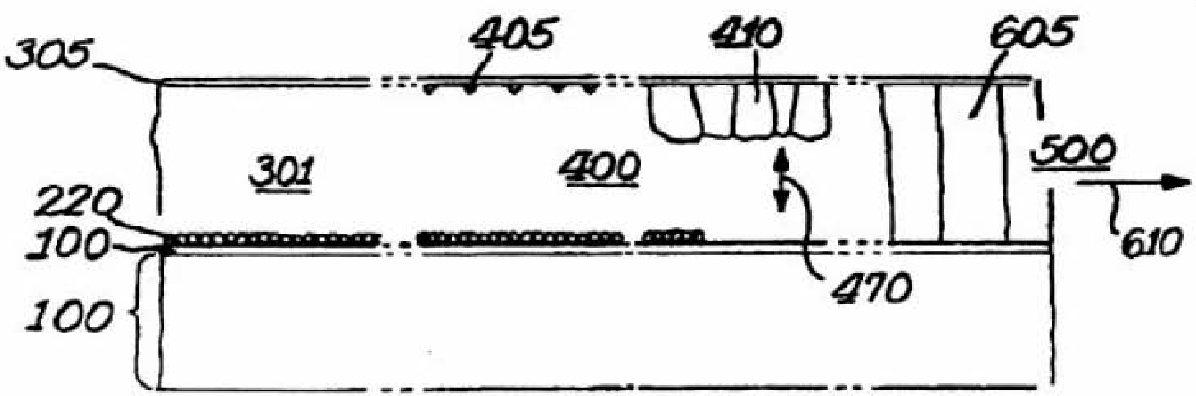
Schematic of RGS growth system

Growth rates from 4 to 9 meters/min

Sheet Growth (B)

Sheet ribbon – General Electric (former Astropower)





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

100 – setter material (a rigid board or a flexible thin belt made of, e.g., quartz graphite, silicon nitride, silicon carbide).

110 – release agent coating, e.g., silicon nitride, silicon oxynitride, silicon carbide, etc.

200 – granulated silicon, grain size: 20 to 1000 microns.

300 – melt zone in Ar/H mixture ambient to minimize Si oxidation

400 – controlled solidification and columnar growth from the top. Nucleation of grains is enhanced by addition of the "coating materials", 305, which can be silicon carbides, nitrides, oxides,..

U.S. Patent 6,111,191 (August 2000)

Comparison of different growth techniques used in silicon technology

Method	Width (cm)	Growth rate, mm/min	Throughput (m^2/day)	Energy use (kWh/m^2)	Typical, best efficiency
Float zone	15	2-4	80	36	<18%, 24%
Czochralski	15	0.6-1.2	30	21-48	<17%, >20%
Cast – directional solidification	69	0.1-0.6	70	9-17	<16.5%, 20%
Ribbon Silicon	8-80 cm	15-20	20	20	15.5%, 18%
Sheet growth (substrate melt shaping)	20	1000-6000	>1000	No data	<12%, 16%

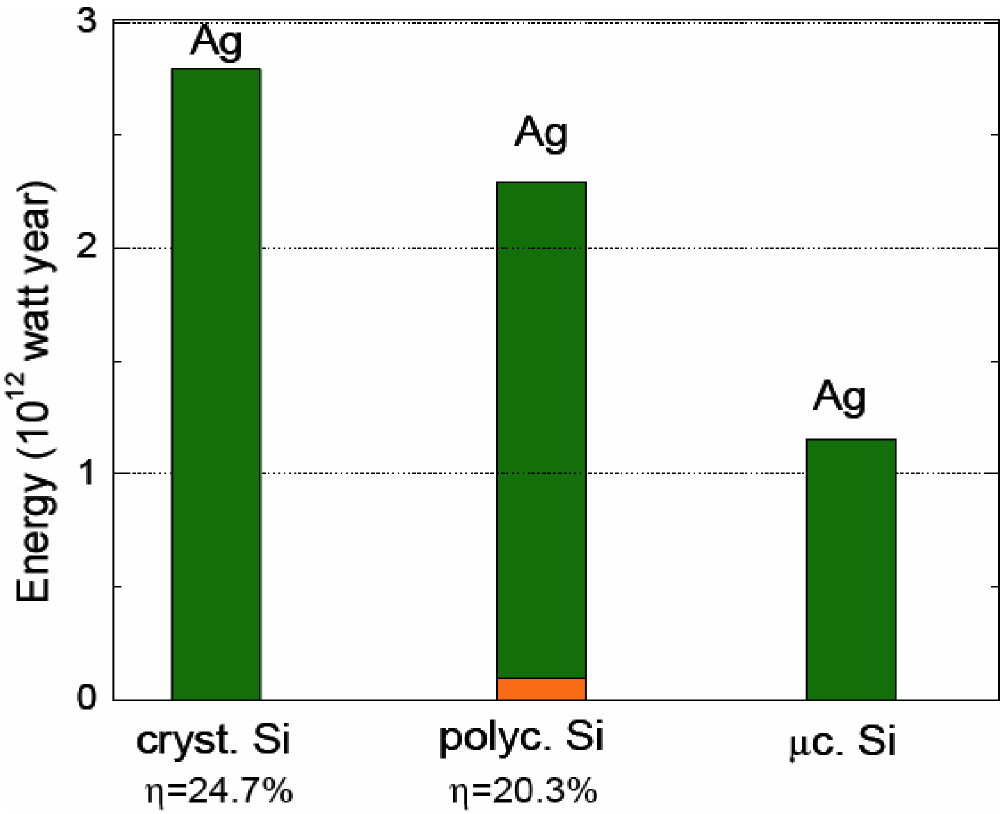
Source for efficiency values: M.A. Green *et al.*, Solar Cell Efficiency Tables, *Progress in Photovoltaics.*

Source for energy use, growth rate, etc.: www.siliconsultant.com . Disclaimer: These numbers are outdated, and may not reflect actual commercial production values.

Materials Availability

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

Not enough silver! New solar cell contact materials needed.



Source: Feltrin, A., A. Freundlich. "Material Considerations for Terawatt. Level Deployment of Photovoltaics." *Renewable Energy* 33 (2008): 180-185. Courtesy of Alex Freundlich. Used with permission.

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

Next Class

- *From wafers to cells.*
- *Intro to thin film technology.*