ME 432 Fundamentals of Modern Photovoltaics

Discussion 31:
Commercial Manufacturing of Silicon & Life Cycle Analysis
4 November 2020
Summary of the Most Common Commercial (or close) PV Technologies Today

**PV Market**

- **Wafer-Based**
  - Monocrystalline Silicon
    - 35% of market
    - Typically use CZ grown wafers
    - Key players: SunPower, REC, Sanyo
    - Commercial Cell Efficiencies: 18-22%
  - Polycrystalline Silicon
    - 50% of market
    - Typically use Bridgman wafers
    - Key players: Q-Cells, Suntech, REC
    - Commercial Cell Efficiencies: 16-18%

- **Thin Film**
  - 15% of market
  - Key players: First Solar (CdTe), Energy Conversion Devices (a-Si)
  - CdTe, a-Si becoming “established”
  - CIGS: “emerging” (start-ups: Nanosolar, Heliovolt)
  - Commercial Cell Efficiencies: 6-11%

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

- **Process flow:**
  Courtesy: Prof. Roland Schindler, Fraunhofer ISE

Feedstock Refining

- Raw Materials
- Si Feedstock
- Wafer
- Cell
- Module
- System
Two Steps

- Metallurgical grade silicon: 98% pure

- Semiconductor grade (or solar grade) silicon
Step 1: Metallurgical Grade Si Production

SiO$_2$ (s) + 2C (s) => Si (l) + 2CO (g)

typically around 98% purity

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

LDK Polysilicon Plant, Xinyu City, China
Step 2: Semiconductor Grade Silicon Production

Standard Silicon Feedstock Refining Process: The “Siemens Process” purification of silicon through gas distillation

1: Mg-Si

2: Silane
   \[ \text{Si} + 3 \text{HCl} \rightarrow \text{SiHCl}_3 + \text{H}_2 \] (300 C)

3: Silane sold to PV, LCD, thin film

4: Most silane used for polysilicon

5: Siemens process at high temperature
   \[ \text{SiHCl}_3 + \text{H}_2 \rightarrow \text{Si} + 3 \text{HCl} \] (1100 C)

6: Rods

7: Rod pieces

8: Loaded ingot crucible
Currently, silicon modules represent less than 20% of the total installed cost of a solar array installation

The rest is balance of systems, installation costs, supply chain costs, ...

Module costs vary with market fluctuations of silicon feedstock availability (polysilicon)

Current ultra-low module costs ($0.25/W) are largely related to low demand and a polysilicon feedstock oversupply

Sept 2012 PV Polysilicon Price Tracker Report:
- Contract prices for 9N silicon at $27.80/kg, spot at $21.90/kg
- 6N to 8N contract at $22.70, spot at $20.10

Nov 2018 PV Polysilicon Price Tracker Report:
- Spot prices for 9N silicon at $9.63/kg
- Spot prices for 6N to 8N at $7.49
Polysilicon Historical Trends

http://www.greentechmedia.com/articles/read/the-global-pv-market-yesterday-today-and-tomorrow
Silicon Wafer Production

- 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)
Single vs. Multi – Crystalline Silicon

Crystalline silicon

Single crystalline silicon
FZ, CZ

Multicrystalline silicon
Cast, ribbon, sheet techniques

Each silicon atom is bonded to four neighbouring atoms.

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.

Slide from A.A. Istratov, Siltronic
Single vs. Multi – Crystalline Silicon

Multicrystalline silicon is very easy to distinguish from single crystalline silicon:
*grains in mc-Si are clearly visible in reflected light*

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*Single-crystalline CZ of FZ wafer*

*Multicrystalline silicon wafer*

Slide from A.A. Istratov, Siltronic
Principles of the CZ Growth Process

Slide from A.A. Istratov, Siltronic
Float Zone Growth

Float-zone silicon growth

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.

Slide from A.A. Istratov, Siltronic

Diameters and rotation speeds of the polysilicon ingot and the growing single crystals can be different
What about multicrystalline Si?

Producing multicrystalline wafers with proprietary technology

1: Solar grade silicon is first put into crucibles...

2: ...and melted in special furnaces

3: It is then cooled from the bottom, crystallization begins...

4: ...and multicrystalline silicon is formed

5: The resulting massive ingot is cut into 16 blocks...

6: ...

7: ...each again sliced into leaf-thin wafers

8: Producing the thinnest wafers in Europe
Other Routes: Ribbon Growth

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

Courtesy: Evergreen Solar
Wafer to Cell Production

Courtesy: Prof. Roland Schindler, Fraunhofer ISE

Cell Fabrication

Raw Materials

Si Feedstock

Wafer

Cell

Module

System

Low-Resistance Emitter

High-Resistance Emitter

Front Contact

SiNₓ

Back contact

n⁺⁺ n⁺ n⁺⁺
p

n⁺⁺ p⁺⁺ p⁺⁺
The Best-Performing Solar Cells Today

Monocrystalline PN Junction Silicon

Crystalline Silicon: Record Holder - PERL, University of New South Wales:

PERL = “Passivated Emitter, Rear Localized”

High quality oxide on front surface for passivation

Rear is “locally diffused” at the contacts to reduce recombination
The Best-Performing Solar Cells Today

Monocrystalline PN Junction Silicon

PERL cell

finger width = 20µm

from pveducation.org
The Best-Performing Solar Cells Today

Monocrystalline PN Junction Silicon

Crystalline Silicon: Other good performers – Sanyo HIT

HIT Solar Cell

- Heterojunction with Intrinsic Thin layer (HIT) Solar Cell
  - Heterojunction: two different semiconductor materials (a-Si:H and c-Si) create the pn-junction
  - Intrinsic: between the p and n type material there is an undoped (“intrinsic”) amorphous Si layers
  - Thin layer: optimum thickness of the intrinsic a-Si:H is about 4 to 5 nm

HIT Solar Cell

- Heterojunction with Intrinsic Thin layer (HIT) Solar Cell

Mono crystalline silicon solar cell  \( \rightarrow \)  HIT® solar cell

Development of HIT solar cell was supported in part by NEDO. (NEDO: New Energy and Industrial Technology Development Organization)

HIT Solar Cell

Crystalline Silicon Solar Cell

Manufactured at 200°C

Manufactured at 900°C

Top Electrode

Bottom Electrode

Amorphous Silicon (0.01μm)

Crystalline Silicon (n-type)

Crystalline Silicon (p-type)
HIT Solar Cell

- Heterojunction with Intrinsic Thin layer (HIT) Solar Cell
  - Band diagram
The Best-Performing Solar Cells Today

Monocrystalline PN Junction Silicon

Crystalline Silicon: SunPower Maxeon

http://www.sunpowercorp.com

Interdigitated Back Contacts: prevent shading losses on the front, contacts can be wider on back to reduce contact resistance

Also includes a oxide passivation layers on both sides, textured front surface, and backside mirror
What about Multicrystalline Silicon?

- Contains many grains, rather than a single crystal
- Fabrication is simpler and cheaper than single crystalline silicon:
  - Single crystalline: Czochralski or FZ growth (35% of market)
  - Polycrystalline: Casting from ingots (50% of market)
  - (Rest of market: thin films)
- Grain size:
  - should be at least a few mm to avoid significant recombination losses from grain boundaries (dislocations)
  - Sometimes grain boundaries also introduce shunting pathways for current flow
- **Cell efficiencies** are slightly lower than mono-crystalline materials (typically 1-2% lower for the same production line)
- **Module efficiencies** are more or less the same as mono-crystalline modules, due to higher packing densities
Packing Density on Module

Single crystal growth is harder and more expensive. Monocrystalline Si comes mainly from CZ growth, as such we are often stuck with circular cells and lower packing density.

pc-Si can be cast into any desired shape; use squares for maximum packing density on the module.

Czochralski growth of Crystalline Silicon
http://www.solarnovus.com

Another technique for making polycrystalline Si wafers: Ribbon Growth. Read all about it, and the bankruptcy of Evergreen Solar, here:

http://evergreensolar.com/en/
Grains of different orientation show up as regions of light and dark on the polycrystalline silicon wafer.

Surface not as uniformly “black” as monocrystalline cells.

Many pc-Si cells utilize instead 1 or 2 anti-reflection coatings (silicon nitride).
Dislocations: Most Deleterious Defect in pc-Si

Dislocation Distribution in an pc-Si Block

Solar Cell: Electrical Performance

Measured minority carrier diffusion lengths

M. Rinio, Ph.D. Thesis

Slides from Prof. Roland Schindler, Fraunhofer ISE
Dislocations: Most Deleterious Defect in pc-Si

Dislocation Distribution in an pc-Si Block

Solar Cell: Electrical Performance

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M. Rinio, Ph.D. Thesis

Slides from Prof. Roland Schindler, Fraunhofer ISE
Module Manufacturing

Courtesy: Prof. Roland Schindler, Fraunhofer ISE

Raw Materials
Si Feedstock
Wafer

Cell
Module
System
Connecting Cells in Series

Since the power of a single solar cell is small, several should be connected together to make a practical generator

Copper ribbons (tabs) are soldered onto the busbars on the front side of one cell ...

... and onto the backside of the next cell

source: http://www.electriworks.com
Each Cell: $V_{oc} = 0.6 \text{ V}$
Module = $0.6 \times 36 = 18 \text{ V}$
Current density = $30-36 \text{ mA/cm}^2$; crystalline cell $100 \text{ cm}^2$, current is $3-3.6 \text{ A}$
The array of cells should be properly encapsulated to withstand exposure to outdoor elements for over 25 years: mechanical loads, rain and humidity, electrical isolation for safety.

**typical layering configuration, all laminated together:**

- **Low Iron Glass**
- **EVA** (ethylene vinyl acetate) with UV stabilizers between cells, top surface, and bottom surface
- **Tedlar**, a composite plastic, acts as a humidity and corrosion barrier.
- **Transparent encapsulant** provides adhesion between cells, top surface, and bottom surface.
- **Transparent surface**: soda-lime, tempered for impact resistance.
Example: SunPower Module

Electrical Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power (+/-3%)</td>
<td>P_{max} 240 W</td>
</tr>
<tr>
<td>Efficiency</td>
<td>\eta 19.3 %</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>V_{mpp} 40.5 V</td>
</tr>
<tr>
<td>Rated Current</td>
<td>I_{mpp} 5.93 A</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>V_{oc} 48.6 V</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>I_{sc} 6.30 A</td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td>UL 600 V</td>
</tr>
<tr>
<td>Temperature Coefficients</td>
<td></td>
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<tr>
<td>Power [\Phi]</td>
<td>-0.38% / K</td>
</tr>
<tr>
<td>Voltage (\Delta V_{oc})</td>
<td>-132.5 mV / K</td>
</tr>
<tr>
<td>Current (\Delta I_{sc})</td>
<td>3.5 mA / K</td>
</tr>
<tr>
<td>NOCT</td>
<td>45°C +/-2°C</td>
</tr>
<tr>
<td>Series Fuse Rating</td>
<td>20 A</td>
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Mechanical Data

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cells</td>
<td>72 SunPower all-back contact monocrystalline</td>
</tr>
<tr>
<td>Front Glass</td>
<td>High transmission tempered glass with anti-reflective (AR) coating</td>
</tr>
<tr>
<td>Junction Box</td>
<td>IP-65 rated with 3 bypass diodes</td>
</tr>
<tr>
<td>Dimensions</td>
<td>32 x 155 x 128 [mm]</td>
</tr>
<tr>
<td>Output Cables</td>
<td>1000mm length cables / MultiContact (MC4) connectors</td>
</tr>
<tr>
<td>Frame</td>
<td>Anodized aluminum alloy type 6063 (black)</td>
</tr>
<tr>
<td>Weight</td>
<td>33.1 lbs. (15.0 kg)</td>
</tr>
</tbody>
</table>

I-V Curve

Current/voltage characteristics with dependence on irradiance and module temperature.

Tested Operating Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>-40°F to +185°F (-40°C to +85°C)</td>
</tr>
<tr>
<td>Max load</td>
<td>113 psf 550kg/m² (5400 Pa) front – e.g. snow; 50 psf 245kg/m² (2400 Pa) front and back – e.g. wind</td>
</tr>
<tr>
<td>Impact Resistance</td>
<td>Hail 1 in (25 mm) at 52mph (23 m/s)</td>
</tr>
</tbody>
</table>

Warranties and Certifications

<table>
<thead>
<tr>
<th>Warranty</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warranties</td>
<td>25 year limited power warranty</td>
</tr>
<tr>
<td>Certifications</td>
<td>Tested to UL 1703: Class C Fire Rating</td>
</tr>
</tbody>
</table>

61 x 31 inch²
E19/240W Panel
IEC Standards for Modules

Qualification tests for verifying module integrity:

IEC (International Electrotechnical Commission) Standard 61215 (v1, 2005) and 61646 (v2, 2008)

Module will qualify if no major failures, visual inspection reveals no damage, electrical power is within 90% of specifications, and isolation is maintained after:

- Ultraviolet exposure using xenon lamps
- Thermal cycling (-40C to 50C, 50 cycles) in climate chamber
- Humidity freeze cycling (thermal cycling with 85% relative humidity)
- Damp heat (1000 hours at 85C and 90% relative humidity)
- Twist test for resistance to torques
- Pressure is applied to test resistance to static mechanical loads
- Hall impact test: module struck by 25-mm diameter ice balls at a speed of 23 m/s
- Outdoor exposure
- Hot spot tests, where module is selectively shaded
Testing Module Performance

Workstation at NREL’s large-area continuous solar simulator test best uses a 25 kW xenon-arc lamp filtered to match the solar spectrum as a Class A solar simulator.
Balance of system (BOS) refers to all components of a photovoltaic system other than the photovoltaic array itself: wiring, switches, inverter, battery

**Off-Grid Installations:**
Charge/discharge controller: directs and controls DC output by array to the battery and inverter

Battery: lead-acid

Inverter: converts DC to AC

**Grid-Connected Installations:**
DC/AC Grid Connected Inverter
180 to 440 VAC to electric utility power grid
Module performance, as tested in a laboratory, can be quite different from module performance on the field. Why?

• Largest single factor is temperature. Modules are tested at 25C. However, typical operation temperatures are around 55-60C.
• Also
  • Angular distribution of light due to the movement of the sun (light does not always fall perpendicular to the module, as is the case with the testing)
  • Small differences in the solar spectrum and irradiance levels (location dependent, air pollution, water content of air, etc)

Example: annual yield for high-efficiency c-Si module at 4 different locations

**Location: Phoenix, AZ (Hot and dry)**
*Expected output based on insolation: 2372 kWh*  
*Observed Output: -23%*

**Location: Miami, FL (Hot and humid)**
*Expected output based on insolation: 1898 kWh*  
*Observed Output: -21%*

**Location: Billings, MT (Cool and dry)**
*Expected output based on insolation: 1483 kWh*  
*Observed Output: -19%*

**Location: Boston, MA (Cool and humid)**
*Expected output based on insolation: 1377 kWh*  
*Observed Output: -18%*
Mismatch losses occur when cells with non-identical properties or cells experiencing different conditions are connected in series.

Example above: Shading losses result in locally lowered $I_{SC}$, reverse biasing of bad cell, and which begins dissipating power. This can result in localized heating, or “hot-spots.”
Long-Term Performance of Modules
Summary of the Most Common Commercial (or close) PV Technologies Today

PV Market

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Life Cycle Analysis

From Wikipedia:

A life-cycle assessment (LCA, also known as life-cycle analysis, ecobalance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

Notable Efforts in LCA of PV Technologies:

- Energy Center of the Netherlands
- Vasilis M. Fthenakis, Brookhaven National Laboratory

**Inputs:**
Module lifetime, wafer thickness, cell/module efficiency, manufacturing yield, energy mix

**Outputs:**
Energy payback time, CO₂ emissions per unit energy generated, toxic releases due to production
Example:
Life Cycle Analysis

A handful of other recent studies exist as well, such as:

Some consistent trends amongst the results:
• Fossil fueled power plants produce electricity with about 440-1100 g CO₂/kWh
• Typical values for nuclear power plants are around 65 g CO₂/kWh, but exhibit a lot of variation
• Renewables range from 9-38 g CO₂/kWh
Energy Payback Time

Energy Payback Time - time in which the energy input during the PV system life-cycle is compensated by electricity generated by the PV system.

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**Energy Payback Time**

*on-roof installation in Southern Europe*

1700 kWh/m².yr irradiation on optimally-inclined modules

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<tr>
<td>mono</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass-EVA-backsheet</td>
<td>14.0%</td>
<td>13.2%</td>
<td>13.2%</td>
<td>10.5%</td>
<td>10.9%</td>
<td>6.6%</td>
<td>8.5%</td>
</tr>
</tbody>
</table>

From: Energy Center of the Netherlands, Life Cycle Analysis Group

m.dewild@ecn.nl
24 November 2009
Energy Payback Time

“The” energy payback time: CdTe PV system

From: M. DeWild, Energy Center of the Netherlands, Life Cycle Analysis Group
Bottom Line on LCA for PV Technology

• Emits 90-95% less CO$_2$ per kWh than coal
• Has ~3 year energy payback time
• Varies minimally amongst different PV technologies
• Largest single source of toxic release to the environment in PV?

Production of batteries, for off-grid systems
See T. Williams et al., Proc. 21st EU-PVSEC (Barcelona, Spain, 2005)