Photovoltaics (PV)
- Direct conversion of sunlight to electricity

Advantages
- Modular (mW to many MW)
- No (or few) moving parts
- Noise and pollution free
- Reliable; low operating costs
- Abundant, indigenous resource (30,000 km² PV for 800 GW)
Solar Cell Structure

Solar cell efficiency (%) = \( \frac{\text{Power out (W) x 100\%}}{\text{Area (m}^2\text{) x 1000 W/m}^2\text{}} \)

10% efficiency = 100 W/m\(^2\) or 10 W/ft\(^2\)
How to select the semiconductor absorber material(s)?

Four-junction device with bandgaps 1.8 eV/1.4 eV/1.0 eV/0.7 eV
Theoretical efficiency > 52%
Best Research-Cell Efficiencies

**Multijunction Concentrators**
- Three-junction (2-terminal, monolithic)
- Two-junction (2-terminal, monolithic)

**Crystalline Si Cells**
- Single crystal
- Multicrystalline
- Thick Si Film

**Thin Film Technologies**
- Cu(In,Ga)Se$_2$
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, micro-, poly- Si
- Multijunction polycrystalline

**Emerging PV**
- Dye cells
- Organic cells (various technologies)

**Efficiency (%)**
- 40
- 36
- 32
- 28
- 24
- 20
- 16
- 12
- 8
- 4
- 0

**Years**
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
Best Research-Cell Efficiencies

**Champion** cells
- 39% concentrator
- 25% crystalline silicon
- 19.5% thin films

Commercial modules
- Typically only 50-65% of these values

**Efficiency (%)**

- Multijunction Concentrators
  - Three-junction (2-terminal, monolithic)
  - Two-junction (2-terminal, monolithic)

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  - Thick Si Film

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  - Multijunction polycrystalline

- Emerging PV
  - Dye cells
  - Organic cells (various technologies)
PV Module Production Experience (or “Learning”) Curve

“80% Learning Curve: Module price decreases by 20% for every doubling of cumulative production"
World PV Cell/Module Production (MW)

Why is there a “silicon problem”?

Four-fold increase in Si use from 2000 to 2005.

Average annual growth rate of 43% over last 5 years; 57% in 2004.

Source: Paul Maycock, PV News, February 2005
PV Technology Options

Flat plates
- Crystalline silicon
- Thin films
- New technologies

Concentrators
- Silicon
- Multijunctions (III-Vs)
### PV Module Production in 2004 by Technology Type *

<table>
<thead>
<tr>
<th>Technology Type</th>
<th>MW</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plates – Single crystal silicon</td>
<td>403.5</td>
<td>33.8</td>
</tr>
<tr>
<td>Cast polycrystalline silicon</td>
<td>669.1</td>
<td>56.0</td>
</tr>
<tr>
<td>Ribbon silicon</td>
<td>41.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Thin film amorphous silicon</td>
<td>64.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Thin film cadmium telluride</td>
<td>13.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Thin film CIGS</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Concentrators – Silicon</td>
<td>0.5</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>1194.7</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

* Source: *PV News*, March 2005

>93%
Crystalline Silicon – Ingots

• Crystal growth developments: larger ingots (to 60 kg CZ, 20 cm diameter), reduced consumables costs (energy, crucibles, ambient gases, hot zones), batch melt recharge for multiple ingots

• PV-specific growth of CZ; starting low-cost FZ

• Highest efficiencies for single crystals: FZ > CZ

  24.7% laboratory cell (FZ)
  16-22% production cells
  13-17% commercial modules
  25-year warranties

• Cast multicrystalline ingots are fastest growing segment of PV industry:
  - Commercial systems available
  - Up to 300 kg ingots

• Extensive development of thermal profiles, impurity distributions, crucibles, automation

• Efficiencies ~10% lower than single crystals

• Opportunities for new crystal growth developments: low-cost FZ and CZ for PV; larger cast ingots; control grain sizes, defects, and impurities
Advent of wire-saw is a significant result of terrestrial PV research:
- Faster than ID saw (1000 vs. 25 wafers/hour)
- Less surface damage
- 250-300 μm thickness, 200 μm kerf routine

Ongoing advances needed:
- Thinner, stronger wires
- Slurry recycling, water-based slurries
- Thin wafer handling in processing
- Detecting microcracks in wafers
**Crystalline Silicon – Ribbons**

- First of new, terrestrial PV technologies to be commercialized
- More than 20 innovative ribbon/sheet growth approaches researched
- Two leading techniques in production:
  - Edge-defined film-fed growth (EFG)
  - String Ribbon

Efficiencies are similar to multicrystalline Si

- Research issues:
  - Yield and throughput (growth rate, ribbon width)
  - Thin ribbons (~100 µm)
  - Thermal stress control
  - Melt replenishment
  - Continuous growth
  - Defects and impurities
High-Efficiency Silicon Solar Cells

- **Buried-contact cell/UNSW**
  - BP Solar – 18.3%
  - Processing/lifetime relations
  - Gettering/passivation of impurities/defects ($\text{Si}_3\text{N}_x\text{H}$ deposition for polycrystalline Si)
  - Feedback to crystal growth
  - High-throughput, low-cost (e.g., rapid thermal) processing
  - Selecting “cheapest” wafer or “cheapest” process will not always result in lowest-cost module

- **HIT cell**
  - Sanyo – 21%

- **Point-contact cell**
  - SunPower – 21.5%

- **Graph**: Cell Efficiency vs. Processing/lifetime relations
  - Conventional Silicon Cell
  - High Lifetime Base
  - Back Surface Field (BSF)
  - Rear Local Contacts (RLC)
  - Passivated Emitter (PE)
  - Selective Emitter (SE)
  - High Lifetime + SE
  - BSF + PE + RCL
  - 21.2%
Crystalline Silicon – Sheets, etc.

- **Silicon Film**™ process (AstroPower, now GE, U.S.)
  - Melt/solidify granular Si on reusable substrate
  - High throughput (3 m/min)
  - Small grain size (~ thickness)
  - Low module efficiency (<8%)

- **RST technique** (Solarforce, France)

- **Spherical Solar**™ Power (Canada)
  - High Si utilization

- **Sliver® cells** (Origin Energy, Australia)
  - High utilization of single-crystal Si wafer
Thin-Film PV Technologies

- Low materials use (~1 \( \mu \text{m} \) vs. ~300 \( \mu \text{m} \) for Si) – direct bandgap absorbers
- Low-cost substrates (glass, stainless steel, plastics)
- High-throughput deposition processes (batch or continuous)
- Lower processing temperatures (less energy use); some non-vacuum
- Fewer processing steps for modules; integral interconnection of cells during film deposition

- Choice of materials dictated by efficiency, materials availability, ease of manufacturing, module reliability, market acceptance

- Leading technologies:
  - Amorphous silicon (a-Si:H)
  - Cadmium telluride
  - Copper indium gallium diselenide (CIGS)

- Future technologies:
  - Thin (polycrystalline) silicon
  - Polycrystalline multijunctions
Thin-Film Amorphous Silicon

- Multi-MW/year in consumer products
- Substrate choices for unique products; lightweight (flexible), building-integrated (roofing tiles, semi-transparent windows)
- Engineered solution for “light-induced degradation”; thin absorber layers and multijunctions

**Stabilized efficiencies:**
- 13% laboratory cell
- 10% best prototype module
- 5-8% commercial modules
- Up to 20-year warranties

- Largest thin-film manufacturing facility: 30 MW/year (United Solar Ovonic, U.S.)

- High-rate deposition (10-100 Å/s vs. 1-3 Å/s)
  - Hot-wire CVD
  - VHF plasma
  - Microwave plasma

- Large research infrastructure leveraged by other applications
- Fundamental understanding of
  - Metastability
  - Roles of hydrogen and impurities
  - Microstructure (amorphous to microcrystalline)
  - Gas phase chemistry and control
  - Low-bandgap materials
**Thin-Film Cadmium Telluride**

- Many scalable deposition approaches for >10% efficiency (high-rate vapor transport, electrodeposition, spraying, close-spaced sublimation, CVD, sputtering, etc.)
- Early consumer products (~1 MW/year)
- Large-scale manufacturing underway:
  - CdS/CdTe deposited in <1 min
  - Module start-to-finish in ~4 hrs
  - Up to 25 MW/year (First Solar, LLC, U.S.)

- Better understanding of film growth is key
  - Thin CdS and alternate buffer/window layers
  - CdTe nucleation and growth; thinner layer
  - Native defects and doping
  - CdS/CdTe interdiffusion
  - Annealing and heat treatment (CdCl\textsubscript{2})
  - Back contacts; role of Cu diffusion

- Compatibility of manufacturing process steps; simplified manufacturing processes

- EH&S issues extensively studied and under control (e.g., recycling) – Cd perception issue?

---

**Diagram:**
- Glass
- EVA (encapsulant)
- CdTe (absorber layer)
- CdS
- Buffer (optional)
- SnO\textsubscript{2}:F (TCO front contact)
- Glass (back glass)

**Layer thickness:**
- 3 mm
- 460 µm
- ~0.3 µm
- ~3 µm
- ~0.1 µm
- ~0.1 µm
- ~0.4 µm
- 3200 µm (3.2 mm)

**Images:**
- As-grown film
- Annealed in CdCl\textsubscript{2} at 450°C, ~20 mins
- AFM images of 0.8 µm film —— 1 µm
Thin-Film CIGS

- Varied deposition approaches: co-evaporation of elements, sputtering/selenization, non-vacuum/wet chemical, electrodeposition
- Glass or flexible substrates (stainless steel, polyimide) for varied products
- Manufacturing of several MW underway, with increasing interest worldwide
  
  19.5% laboratory cell
  18.6% with ZnS (“Cd-free” cell)
  13% best prototype module
  9-11% commercial modules
  >10-year warranties

- Understanding of film growth, microstructures, defects, and device physics – complex but “tolerant” to processes
- Recipe for high-efficiency devices: Cu-rich step (large grains) followed by In-rich step (for target composition)
- Role of Na (necessary); higher bandgap alloys (Ga, S)
- Alternate, Cd-free window/buffer layers
- Process controls in manufacturing for uniform composition and thinner films (<1 μm); higher throughput and yield

SEM images of stages of film growth (a → d)
Thin-Film PV Manufacturing and Applications

United Solar Ovonic (U.S.)
First Solar (U.S.)
Shell Solar (U.S.)
Global Solar (U.S.)
Thin-Film PV Manufacturing and Applications

Major challenges for technologies:

- **Module reliability for >20 years outdoors**
  - Accelerated life testing
  - Hot and humid climates testing
  - Advanced packaging materials

- **Market acceptance of products**
  - Niche, high-value applications
  - Power modules with demand > supply

- **Competition from crystalline silicon**
  - Can thin films stay ahead of ongoing improvements in c-Si?
  - Financial commitment of investors
New Thin-Film PV Research Directions

**Thin Crystalline Silicon**
- Microcrystalline Si bottom cells for a-Si:H multijunctions – in production
- Thin polycrystalline silicon (<10 μm) on low-cost substrates
  - Light-trapping designs
  - Many novel approaches (e.g., “lift-off” from re-usable wafers, recrystallizing amorphous or small-grained films, etc.)

**Transparent Conductors**

- **n-type**
  - ITO*
  - SnO₂: F, Cl, Sb*
  - ZnO: Al, B, Ga, In*
  - CdO: F
  - Cd₂SnO₄
  - In₂O₃
  - In₂O₃: Mo
  - Zn₂SnO₄
  - * Commercial Products

- **p-type**
  - CuAlO₂
  - CuInO₂
  - Cu₂SeO₂
  - ZnO: N, Ga

**Heterojunction Partners**

- **“Buffer Layers”**

<table>
<thead>
<tr>
<th>Material</th>
<th>Process</th>
<th>Material</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga₂S₃</td>
<td>PVD</td>
<td>SrF₂</td>
<td>PVD</td>
</tr>
<tr>
<td>Ga₂Se₃</td>
<td>PVD</td>
<td>ZnInₓSeᵧ</td>
<td>PVD</td>
</tr>
<tr>
<td>(InGa)₂Se₃</td>
<td>PVD</td>
<td>ZnₓMgₙO</td>
<td>Sputter</td>
</tr>
<tr>
<td>In(HO)₃</td>
<td>CBD</td>
<td>ZnO</td>
<td>ALD, MOCVD</td>
</tr>
<tr>
<td>InₓSeᵧ</td>
<td>PVD</td>
<td>Zn(O,S,OH)ₓ</td>
<td>CBD</td>
</tr>
<tr>
<td>In₂Se₃</td>
<td>ALD</td>
<td>ZnS</td>
<td>CBD, PVD</td>
</tr>
<tr>
<td>SnO₂</td>
<td>CBD</td>
<td>ZnSe</td>
<td>Sputter</td>
</tr>
<tr>
<td>Sn(S,O)₂</td>
<td>CBD</td>
<td>ZrO₂</td>
<td>CBD</td>
</tr>
</tbody>
</table>

ALD - atomic layer deposition; CBD - chemical bath deposition; PVD - physical vapor deposition

**Key components for all thin-film technologies – opportunities for crystal growth research**
Polycrystalline Thin-Film Multijunctions

- Success of CIGS and CdTe is motivating new research toward higher efficiencies in thin films:
  - >25% solar cells
  - >20% modules

- Potential to improve flat-plate silicon efficiency with appropriate top cell or develop top cell/thin Si tandem

- Key research questions: efficient top cell (>15%) with bandgap of 1.5-1.8 eV; tunnel-junction interconnects; compatibility of film growth processes; monolithic versus mechanical-stack designs

- Early results validate some of the concepts:
  - 12.7% CdTe top cell (>50% transmission)
  - 9.7% mechanically-stacked CGS/CIS
  - 5.1% CGS/thin polycrystalline Si tandem
  - All-sputtered CdTe/HgCdTe tandem (1.3%)
  - 21.5% CIGS cell under concentration (14 suns)

- Significant research needed to accomplish goals
Concentrator PV Technologies

- Manufacturability demonstrated for all system components:
  - Low-concentration, line focus
  - High-concentration, point focus
  - Refractive and reflective optics
  - Secondary optics; passive/active cooling
  - Tracking and supports; installation
  - High-efficiency cells (Si, III-Vs) are in production – best cell efficiencies:
    - 27% Si (up to 400X)
    - 28% GaAs (up to 1000X)
    - 39% GaInP$_2$/Ga(In)As/Ge triple-junction (up to 600X)
    - 37.9% GaInP$_2$/GaAs/GaInAs at 10X

- Commercial modules: ~17% (Si)
- Best prototype modules: >20% (Si), >24% (GaAs), 28% (GaInP$_2$/GaInAs/Ge), >20% (Si dense-array)

- Predictable, low costs for large-scale manufacturing and deployment
  - Applications are limited to areas of high direct (not diffuse or global) solar radiation
  - Many of today’s distributed PV markets are not suitable for concentrators (>25 kW units)
High-Efficiency Concentrator Cells

- Multijunction devices offer better utilization of solar spectrum
  - Highest efficiencies in III-V materials
  - Opportunity to tailor bandgaps
  - Lattice-matched or mismatched growth
  - Complex crystal growth challenges – alloying, doping, control of defects and impurities, compatibility and stability of successive layers, passivating layers and tunnel junctions
  - Commercial growth systems (MOCVD) produce cells for space markets
  - Early terrestrial tests promising

- Adding 1-eV cell in above structure should result in >40% efficiency (GaInAsN?)
- 5-junction and 6-junction cells are being investigated – easier to match lower currents but get higher voltages (mostly for space)

- Potential to improve silicon cell efficiency with appropriate top cell – recent results on lattice-matched GaNPAs-on-Si (with GaP tunnel junction) look promising
Future Generation PV Technologies

- Opportunities for innovation – ultra low cost, ultra high efficiencies, new materials, new device physics
  - Nanoparticle precursors
  - Exciton cells (dye, polymer, organic, small molecules, etc.)
  - Quantum dots, hot-carrier, impurity band cells
Future Generation PV Technologies

- Opportunities for innovation – ultra low cost, ultra high efficiencies, new materials, new device physics
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  - Exciton cells (dye, polymer, organic, etc.)
  - Quantum dots, hot-carrier, impurity band cells

The “success” of PV does not require these ultimate discoveries – but scientific research and discovery are the foundations for technological progress.
What is the future for PV?

• Market needs
• Technology projections
  - Crystalline silicon
  - Thin films/Concentrators
  - New technologies
• Solar future
• Market incentive programs – and government policies – are key to continued progress:
  - Feed-in tariff (Germany, Spain, etc.)
  - Subsidies – now only 15% (Japan)
  - Portfolio standards/buydowns/tax credits (U.S.)
Existing State RPS Requirements: 18 States and Washington, D.C.

- CA: 20% by 2010
- NV: 15% by 2013
- NM: 10% by 2011
- AZ: 1.1% by 2007
- HI: 20% by 2020
- WI: 2.2% by 2011
- TX: 2880 MW by 2009
- PA: 8% by 2020
- MD: 7.5% by 2019
- NY: 24% by 2013
- CT: 10% by 2010
- DC: 11% by 2022
- ME: 30% by 2000
- MA: 4% new by 2009
- RI: 16% by 2019
- NJ: 6.5% by 2008
- MN (Xcel): 825 MW wind by 2007 + 10% by 2015
- IA: 105 aMW
- CO: 10% by 2015

www.dsireusa.org
# Build-Up of PV Value In California

<table>
<thead>
<tr>
<th>Category</th>
<th>Value (¢/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of Health Benefits*</td>
<td>0.02 - 0.04</td>
</tr>
<tr>
<td>Value of Avoided NO\textsubscript{x} Emissions*</td>
<td>0.01 - 0.03</td>
</tr>
<tr>
<td>Value of Avoided CO\textsubscript{2} Emissions*</td>
<td>0.33 - 1.77</td>
</tr>
<tr>
<td>Value of Avoided Water Use</td>
<td>0.01 - 0.05</td>
</tr>
<tr>
<td>Value of Fossil Fuel Price Hedge</td>
<td>0.41 - 0.95</td>
</tr>
<tr>
<td>Value of Grid Support*</td>
<td>0.09 - 0.28</td>
</tr>
<tr>
<td>Value of Deployment Ease and Speed</td>
<td>Site Specific</td>
</tr>
<tr>
<td>Avoided Generation and T&amp;D Losses*</td>
<td>0.52 - 1.36</td>
</tr>
<tr>
<td>Avoided Generation Fuel Cost (Natural Gas)</td>
<td>3.24 - 9.71</td>
</tr>
<tr>
<td>Avoided Generation Variable Operation &amp; Maintenance Cost*</td>
<td>0.00 - 0.08</td>
</tr>
<tr>
<td>Avoided Distribution Cost* (All Costs Allocated to Summer Peak)</td>
<td>0.19 - 2.95</td>
</tr>
<tr>
<td>Avoided Transmission Cost* (All Costs Allocated to Summer Peak)</td>
<td>0.04 - 0.72</td>
</tr>
<tr>
<td>Avoided Generation Capacity Fixed Operation &amp; Maintenance Cost*</td>
<td>0.19 - 0.44</td>
</tr>
<tr>
<td>Avoided Generation Capacity Capital Cost*</td>
<td>2.73 - 4.01</td>
</tr>
</tbody>
</table>

(65% Effective Load Carrying Capacity applied to all Avoided Capacity Costs)

**RANGE OF TOTAL VALUE OF PV:** 7.8 - 22.4 ¢/kWh
PV Module Production Experience (or “Learning”) Curve
... The “near-term” scenario

Based on continued progress in and dominance of crystalline silicon technology

* Future-year markers are based on 25% annual growth rates (expect <25% in this scenario)
PV Module Production Experience (or “Learning”) Curve

... The “mid-term” scenario

Based on successful progress in thin films and/or concentrator technologies

* Future-year markers are based on 25% annual growth rates (expect >25% in this scenario)
PV Module Production Experience (or “Learning”) Curve ... The “long-term” scenario

Based on discovery and progress in new technologies

* Future-year markers are based on 25% annual growth rates (expect >>25% in this scenario)
Solar Decathlon II
October 7-16, 2005
### Are there enough materials for energy-significant PV production?

<table>
<thead>
<tr>
<th>Technology</th>
<th>Material</th>
<th>World Production^a</th>
<th>Materials Required^ab</th>
<th>% of Current Production</th>
<th>Annual Growth Needed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline silicon</td>
<td>Purified silicon</td>
<td>25,000 MT/yr(^b)</td>
<td>130,000 MT</td>
<td>520%</td>
<td>3.7%(^c)</td>
</tr>
<tr>
<td></td>
<td>Silver (grids/cell pads)</td>
<td>20,000 MT/yr</td>
<td>6,000 MT</td>
<td>30%</td>
<td>0.53%</td>
</tr>
<tr>
<td>Thin-film Cu (In, Ga) Se(_2) alloys</td>
<td>Indium</td>
<td>250 MT/yr (byproduct)</td>
<td>400 MT</td>
<td>160%</td>
<td>2.0%(^d)</td>
</tr>
<tr>
<td></td>
<td>Selenium</td>
<td>2,200 MT/yr</td>
<td>800 MT</td>
<td>36%</td>
<td>0.6%(^e)</td>
</tr>
<tr>
<td></td>
<td>Gallium</td>
<td>150 MT/yr</td>
<td>70 MT</td>
<td>47%</td>
<td>0.9%(^f)</td>
</tr>
<tr>
<td>Thin-film cadmium telluride</td>
<td>Tellurium</td>
<td>450 MT/yr (2,000 unused byproduct)</td>
<td>933 MT</td>
<td>38% (of total, including unused)</td>
<td>2.2%</td>
</tr>
<tr>
<td></td>
<td>Cadmium</td>
<td>26,000 MT/yr (byproduct)</td>
<td>800 MT</td>
<td>3%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Thin-film silicon</td>
<td>Germanium</td>
<td>270 MT/yr (3,200 unused byproduct)</td>
<td>40 MT</td>
<td>1% (of total, including unused)</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

^a Necessary production for each type of PV technology to produce 20 GW/yr by 2050.

^b Metric Tons

^c Elemental silicon is not constrained by supply; current production is low because of low demand.

^d Indium is a byproduct of zinc, which has been growing at 3%/yr for 50 years. Indium growth will probably exceed demand because of growth in zinc extraction. Indium production would only have to increase 2%/yr to keep pace with demand.

^e Selenium is a byproduct of copper; an increase of only 0.16%/yr would keep pace with demand.

^f Gallium is not constrained by supply; current production is low because of low demand.
PV Manufacturing R&D Cost/Capacity (DOE/U.S. Industry Partnership)

2003 Data
13 PV Manufacturing R&D participants with active manufacturing lines in 2003
Direct module manufacturing cost only (2003 Dollars)
Silicon Feedstock – Is there a problem?

- Historically, PV industry used “low-cost” end of electronic-grade Si
- “Scraps” and “off-spec” approx. 5% of total (<$20/kg)
- In 2003, ~9,000 MT for PV out of ~26,000 MT silicon produced

- With annual growth of 10% in IC industry and 35% in PV industry, shortages are expected by 2005
- Adding new EC capacity requires price of >$60/kg
- “Solar-grade” silicon by modified Siemens process:
  - Fluidized-bed reactor (granular feedstock)
  - Silicon tube to replace slim-rod (high-rate dep’n)
  - ~$30/kg should be possible and be available
- Feedstock only ~5%-7% of PV system cost today

- Purifications of MG-silicon possible (acid-leaching, slagging, alcohol dissolution, reactive gas blowing, directional solidifications, etc.)
- Not likely to result high-enough quality for high-efficiency solar cells
- Area for extensive materials research