PV Technology to Change the World

Synergy of Photovoltaics from Space to Terrestrial Applications

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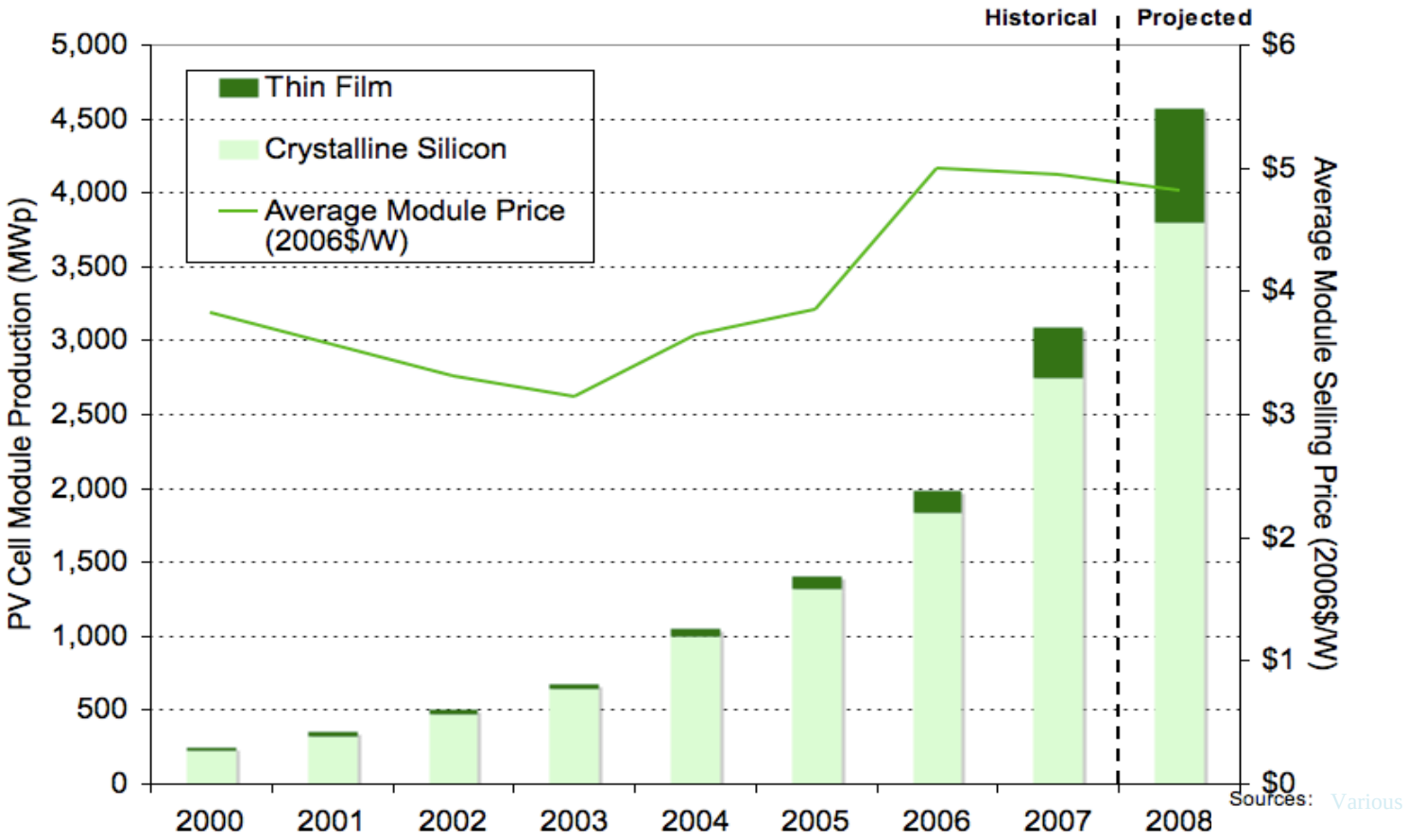
The PV market has enjoyed strong growth over the last 5 years

PV module production has grown significantly, but the rise in silicon feedstock prices has temporarily reversed the historical trend of declining average module selling prices

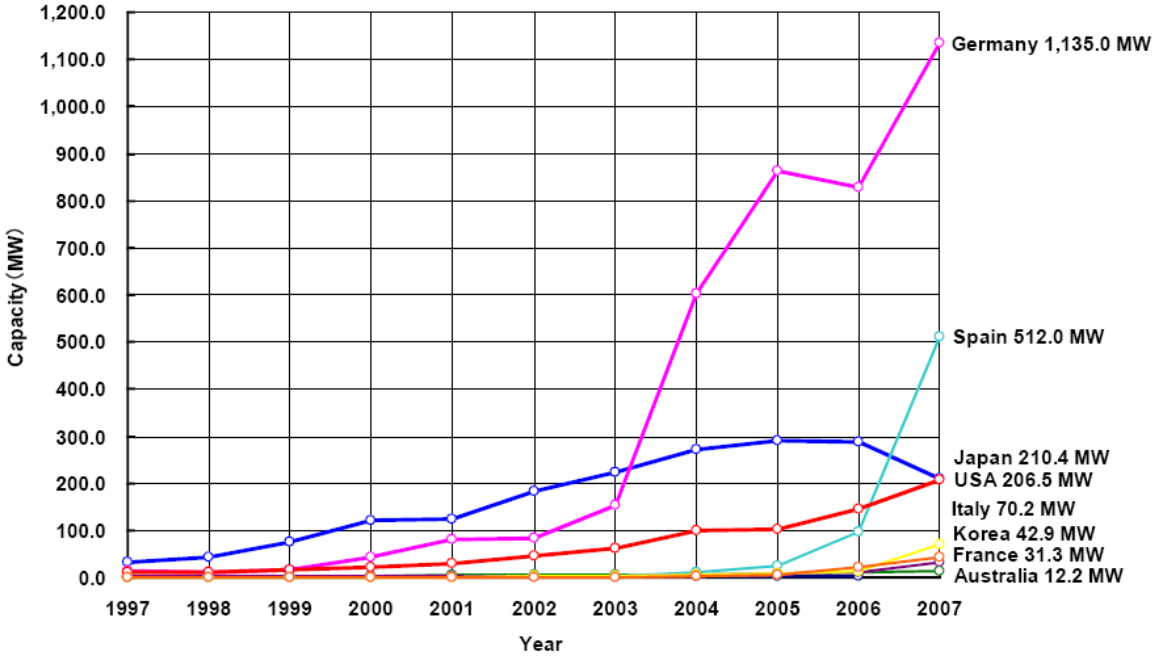


The PV industry is being driven by markets outside the US

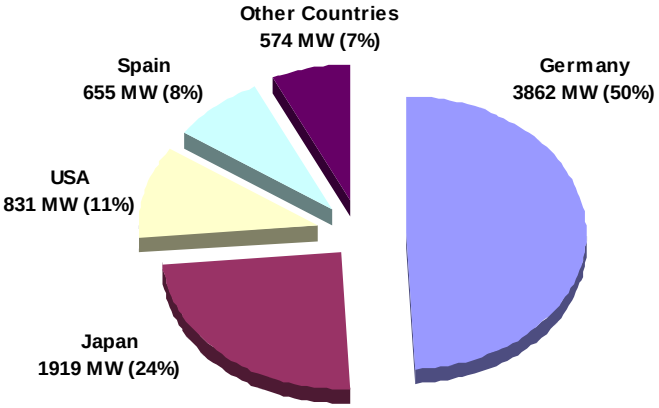
At the end of 2007, cumulative installed PV capacity was estimated to be 7,800 MW world-wide, 93% of which is located in Germany, Japan, the US and Spain

- 7,200 MW is grid-connected
- In addition, there is 430 MW of installed concentrating solar power (CSP),
  including 419 MW in the US and 11 MW in Spain

Trends in Annual Installed PV Capacity in IEA-PVPS Member Countries, through 2007



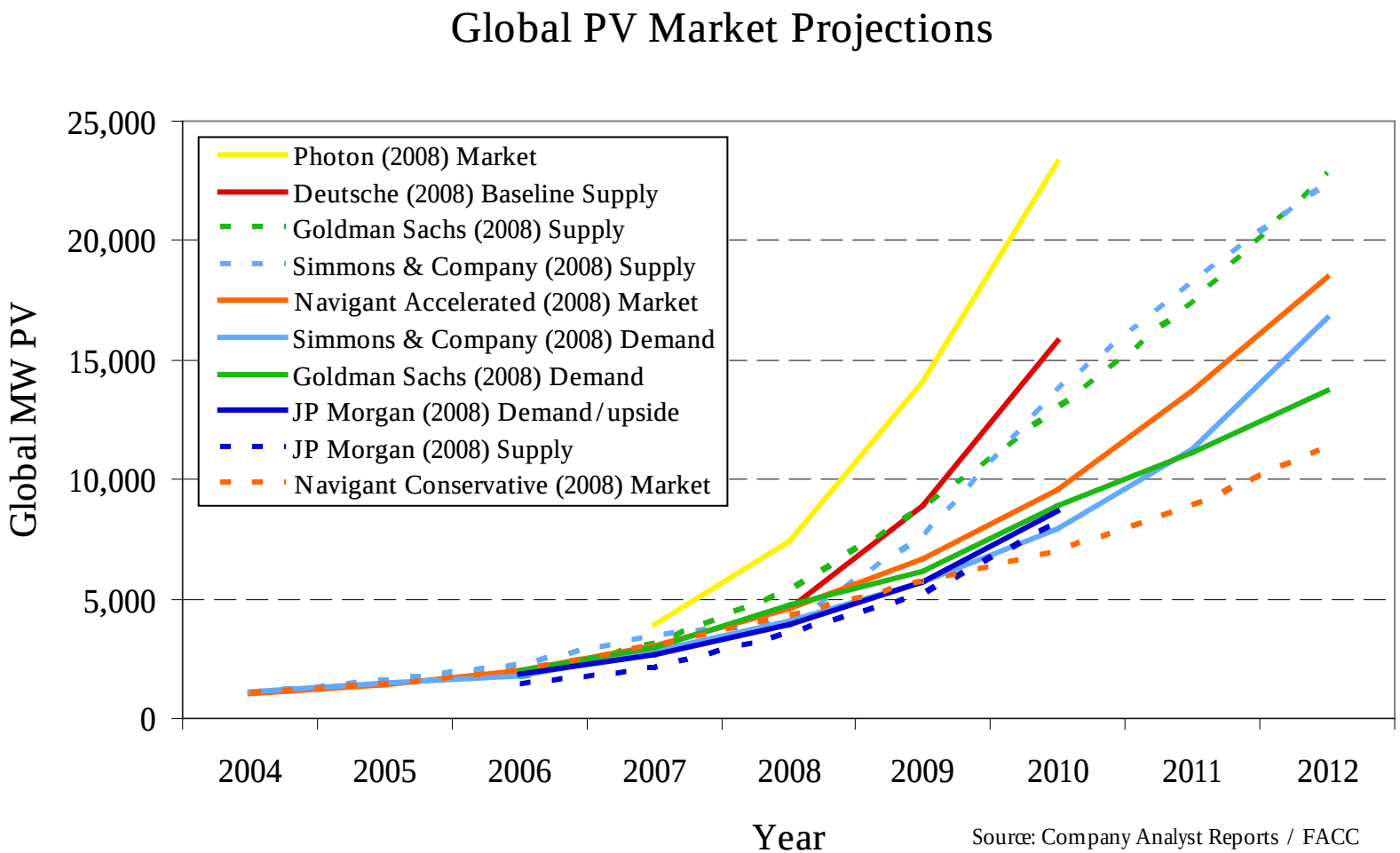
Cumulative Installed PV Capacity through 2007



Source: IEA

There has been considerable uncertainty on PV market size growth projections

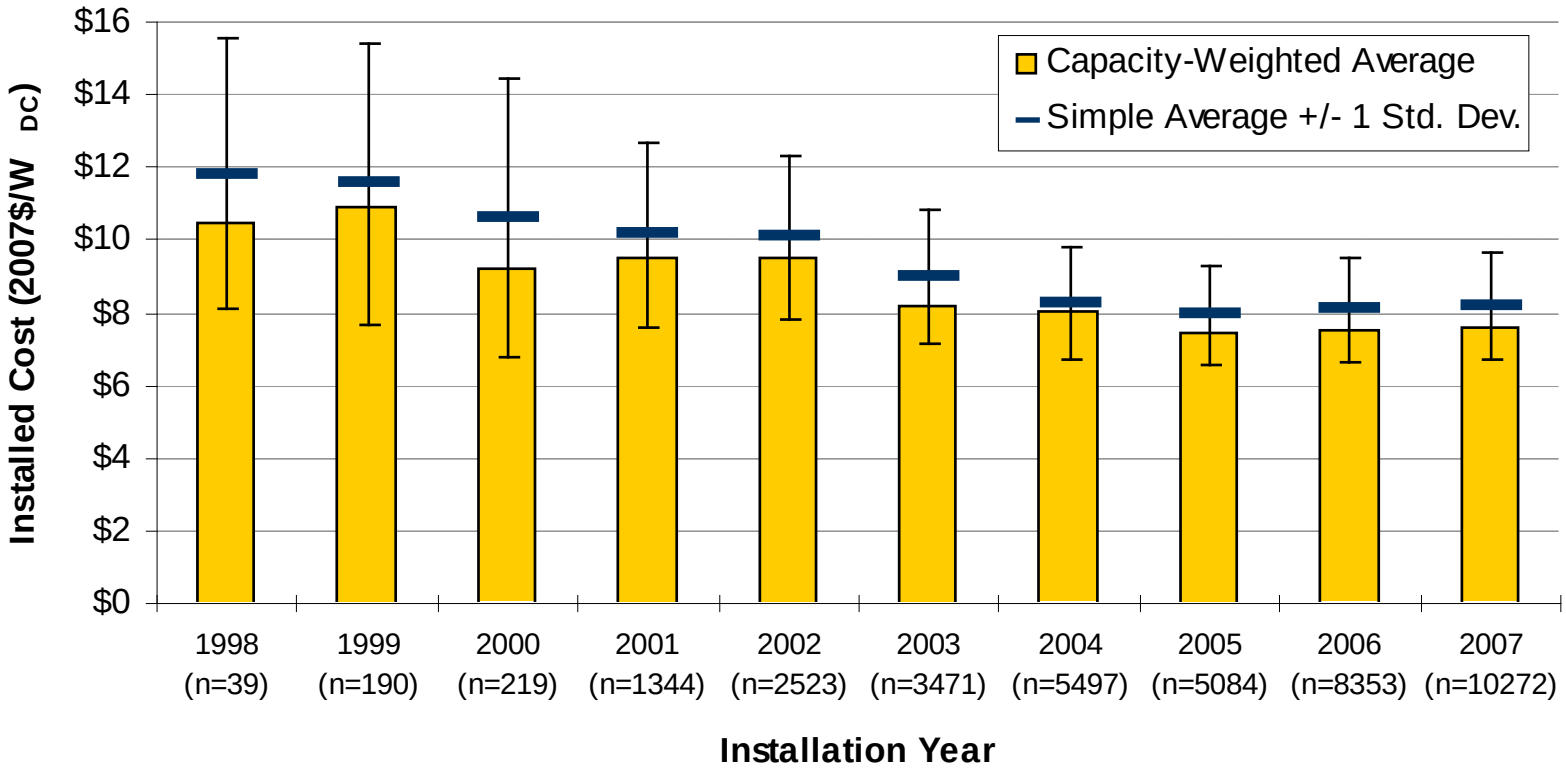
This uncertainly has been compounded by the recent global economic slowdown and financial crisis



Source: Company Analyst Reports / FACC

While significant progress has been made, PV system costs must be reduced by >2-3X to reach wide-spread grid parity

Average annual reduction of $0.32/$W_{DC}$ in real 2007$ (3.1%/yr real, 4.8%/yr nominal) from 1998-2007, but no apparent reduction in costs since 2005



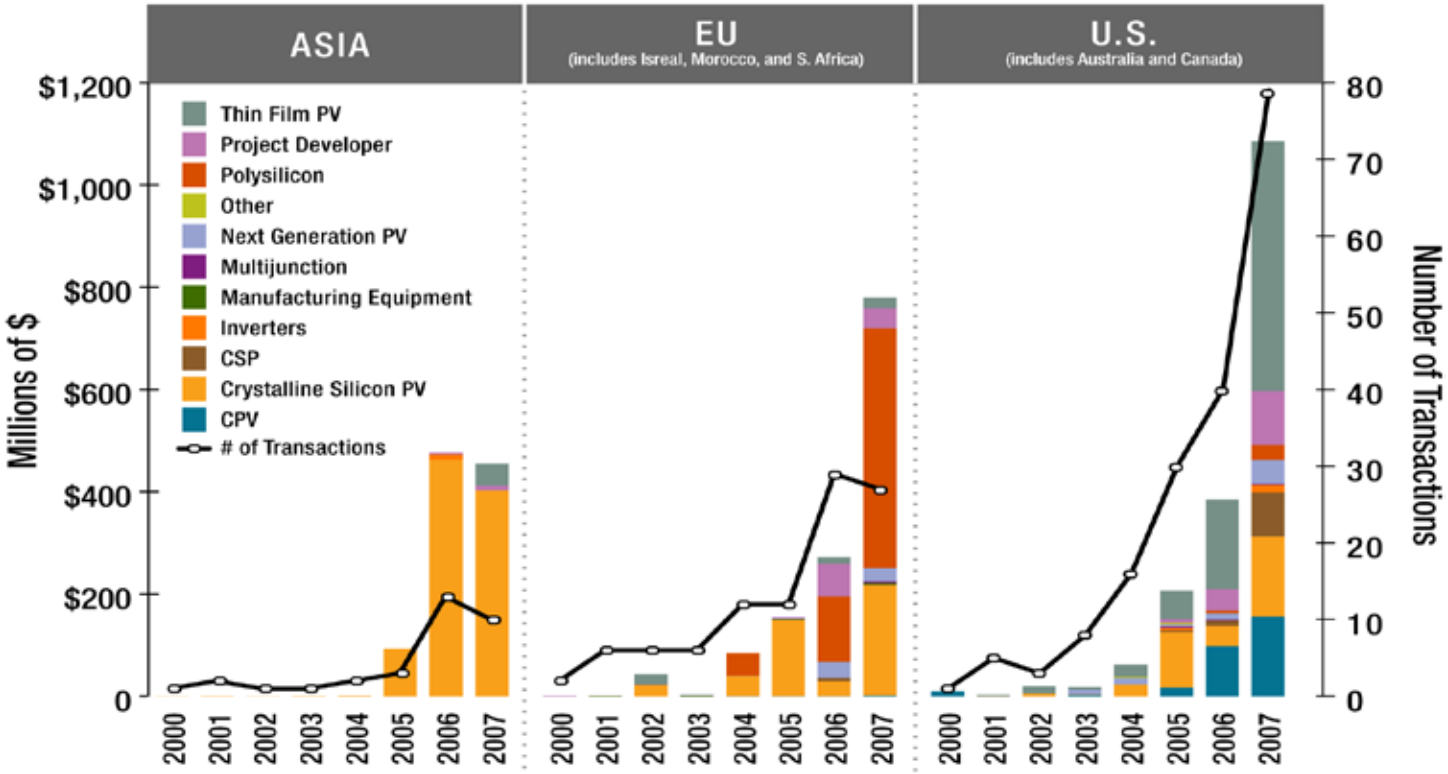
Souce: Wiser, Barbose, Peterman (LBNL)

Global private investments in solar, by region and technology

The US is the most diversified in solar technologies receiving VC and PE financing, with substantial investment in thin film PV, as well as CPV and CSP

- In Europe, most of the funding has been to polysilicon and c-Si PV companies
- In Asia, almost all investment has gone to c-Si PV

Global Venture Capital and Private Equity Investments by Solar Technology

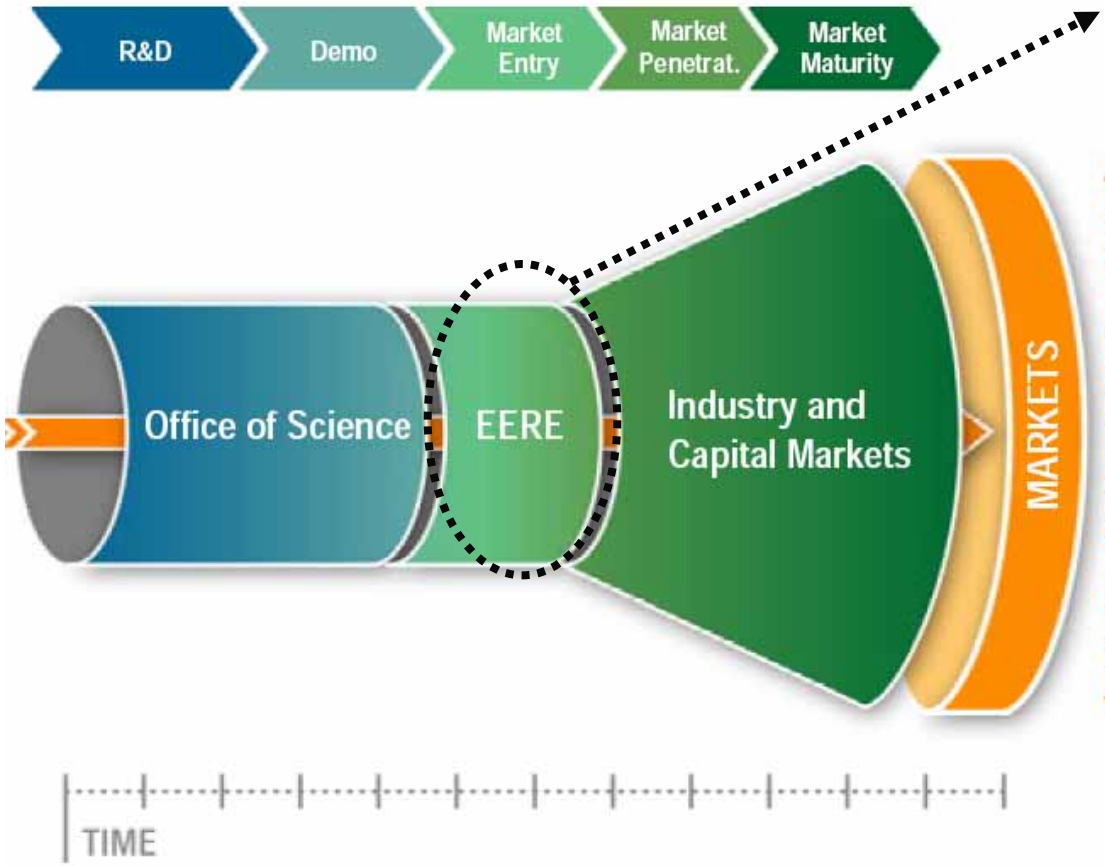


Source: NEF / NREL / FACC

U.S. Department of Energy Budget Breakdown

U.S. Department of Energy

Annual Budget: $23.9 Billion (FY08)



Energy Efficiency, Renewable Energy (EERE)

Annual Budget: $1.7 Billion (FY08)

10 Programs

Energy Efficiency

- Building Technologies
- Weatherization & Intergovernmental
- Industrial Technologies
- Federal Energy Management
- Vehicles

Renewable Energy

- Wind & Hydropower
- Biomass
- Geothermal
- Hydrogen, Fuel Cells & Infrastructure
- and ….

Solar Energy Technologies Program (SETP)

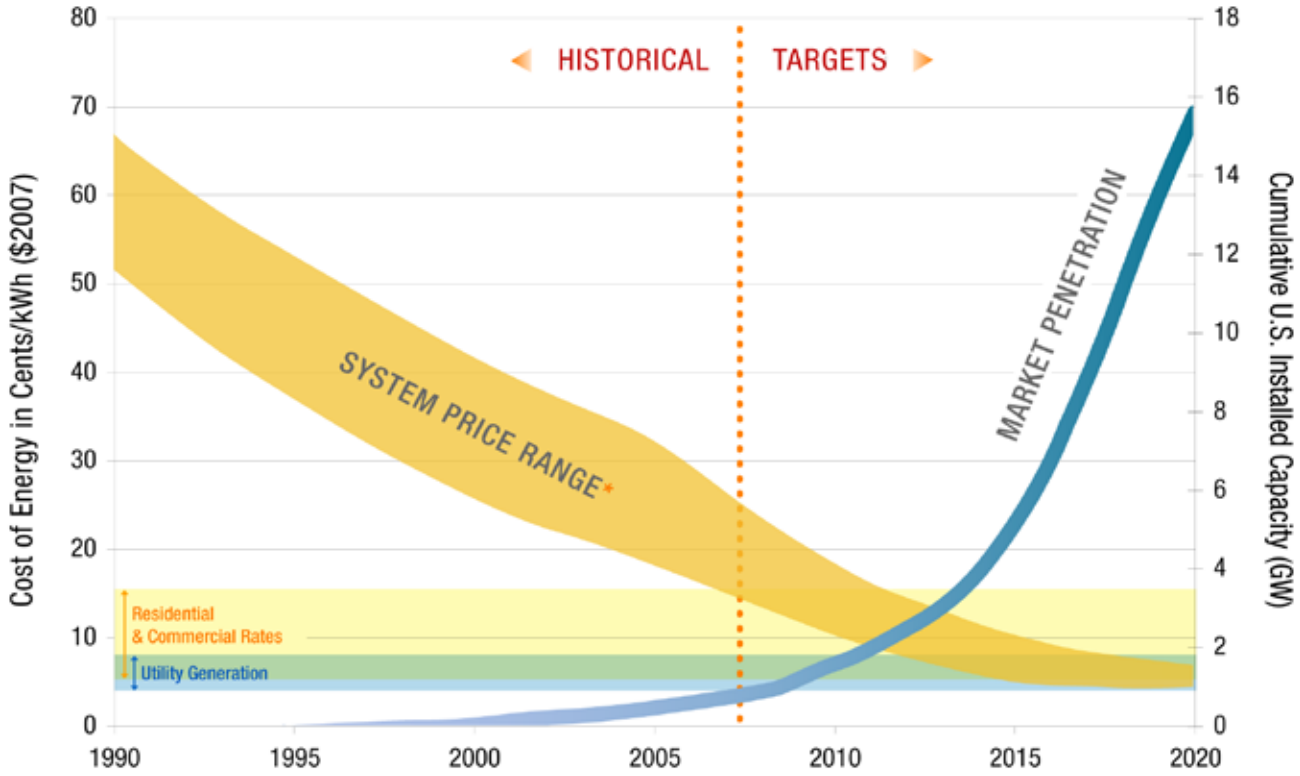
Annual Budget: $168 Million (FY08)

~20 Staff (incl. contractors)

The mission of DOE's Solar Program is to

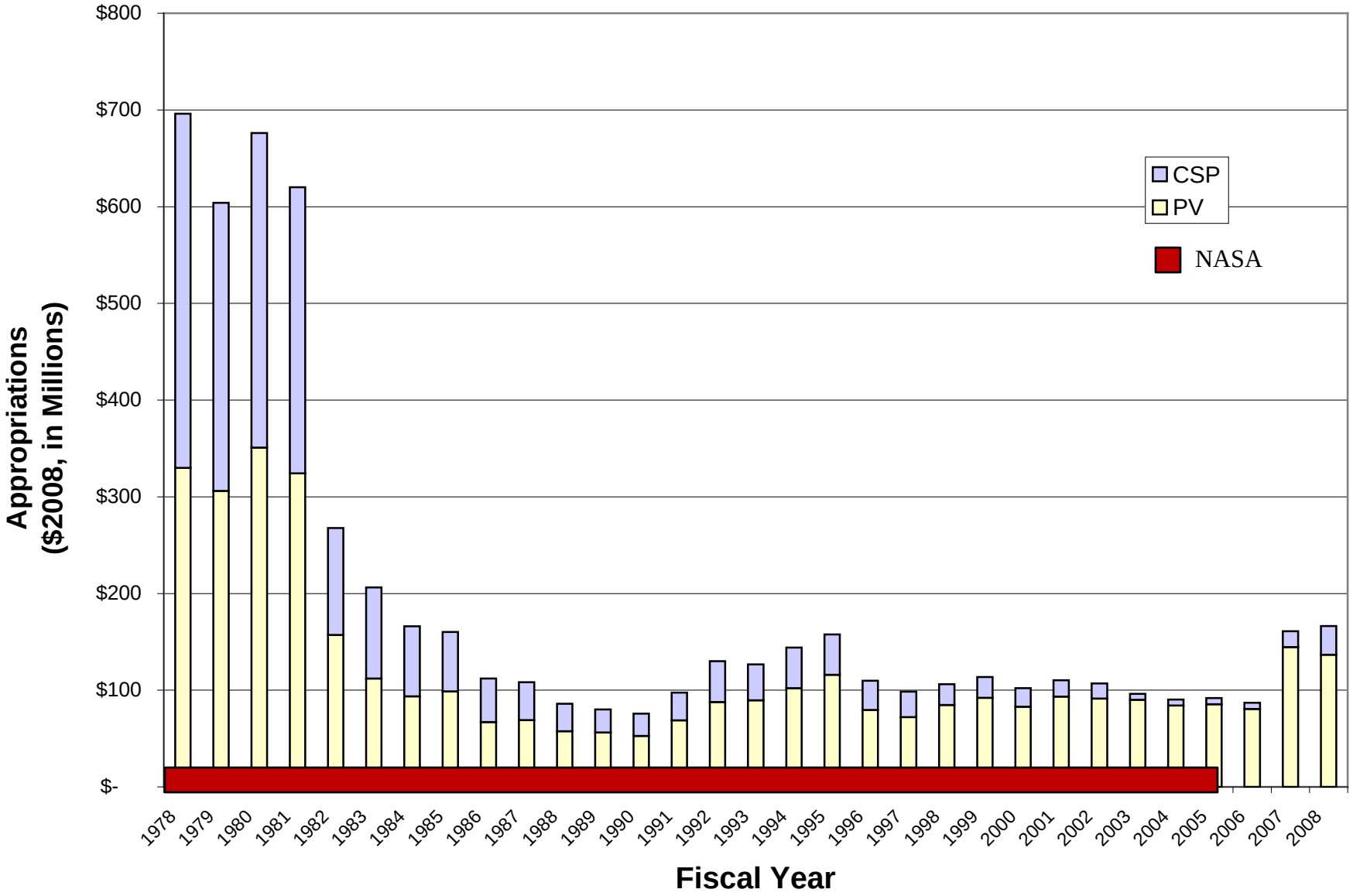
Reach grid parity by 2015 and accelerate the wide-spread adoption of solar electric technologies across the United States

The SETP is focused on enabling high penetration of solar energy technologies and achieving grid parity by 2015



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8 - 16.7	23 - 32	13 - 18	8 - 10
Commercial	5.4 - 15.0	16 - 22	9 - 12	6 - 8
Utility	4.0 - 7.6	13 - 22	10 - 15	5 - 7

Solar Program Budget History



Photovoltaic and Space Environments Program

•High Efficiency III-V Photovoltaic Development

Budget: ‘00(720K);‘01(535K); ‘02 (500K); ‘03 (500K); ‘04 (980K); ‘05 (790K); ‘06(0)

• Advanced Thin Film Technology

Budget:‘00 (690K);‘01(750K); ‘02 (500K);‘03 (500K**);** ‘04 (1120K);‘05 (840K); ‘06(0)

•Space Environmental Effects

Budget:‘00 (650K);‘01 (1070K);‘02 (700K); ‘03 (700K);‘04 (1327K); ‘05(650K);’06(0)

•Measurement and Calibration

Budget:‘00 (NA); ‘01 (500K); ‘02 (500K); ‘03 (500K); ‘04(1030K); ‘05 (650K); ‘06(0)

•Advanced Photovoltaic Concepts

Budget: ‘00 (90K) ‘01 (340K)

Extended Temperatures

Budget: ‘02 (200K); ‘03 (200K); ‘04 (526K); ‘05 (0)

Advanced Blanket and Array Technology

Budget: ‘02 (175K); ‘03 (175K); ‘04 (416K); ‘05 (ECPs 114K*); ‘06(0)

Quantum Dot Technology

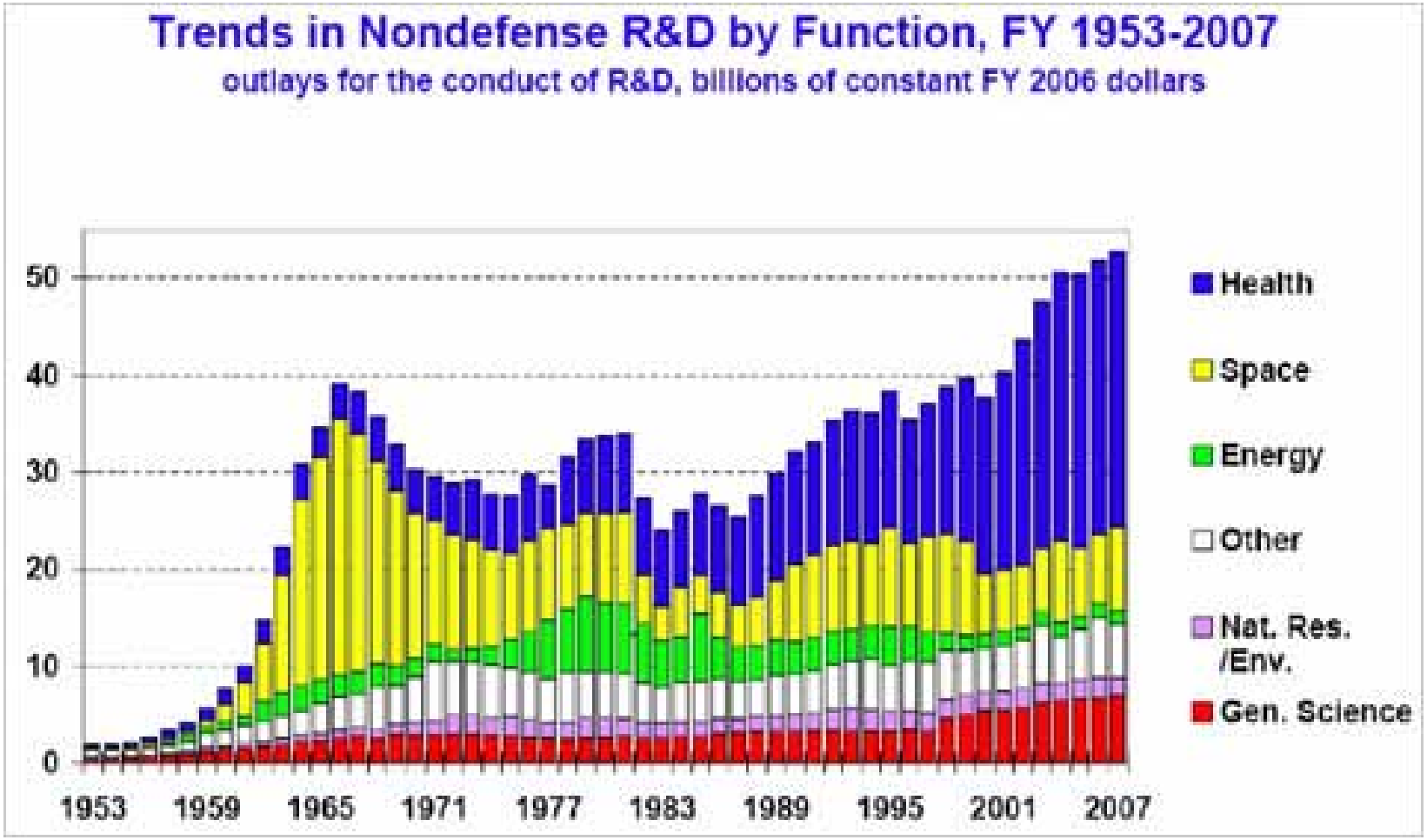
Budget: ‘02 (200K); ‘03 (200K); ‘04 (627K)

Nanomaterials and Nanostructures for Space Photovoltaics

Budget: ‘05 (ICP 557K); ‘06(0)

(blue numbers are procurement only) (red numbers include cost of civil service personnel)

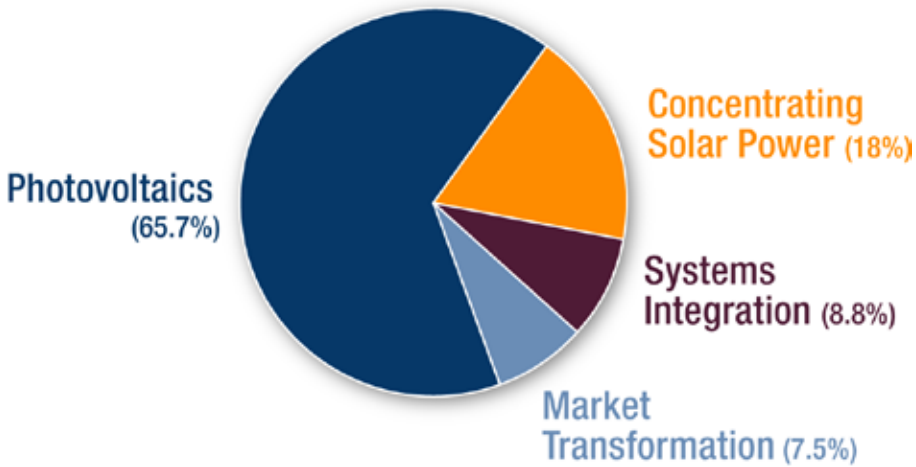
***In-house only**



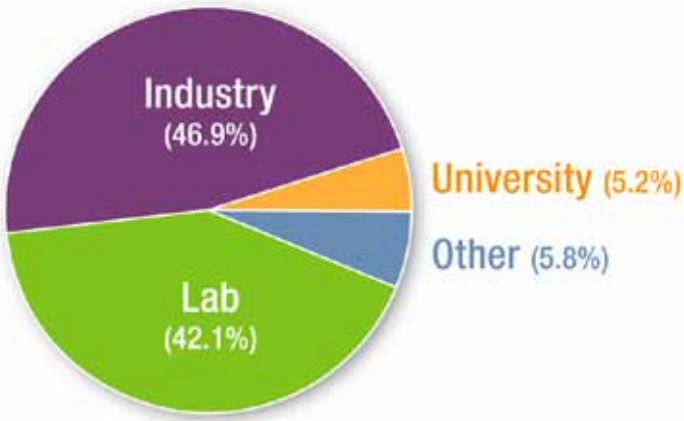
Andrew C. Revkin, NYTimes,
data from American Association for the Advancement of Science

FY09 Projected Solar Budget

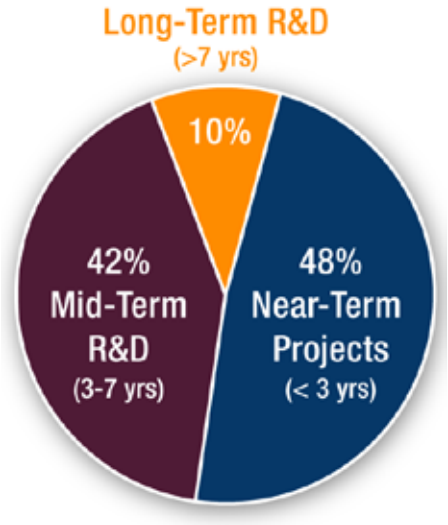
By Technology



By Recipient



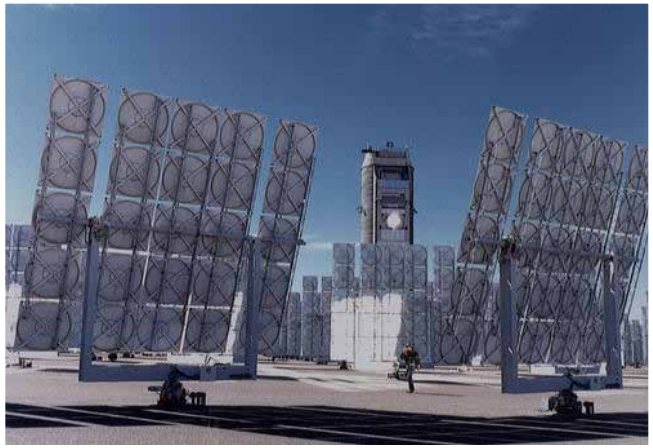
By Term



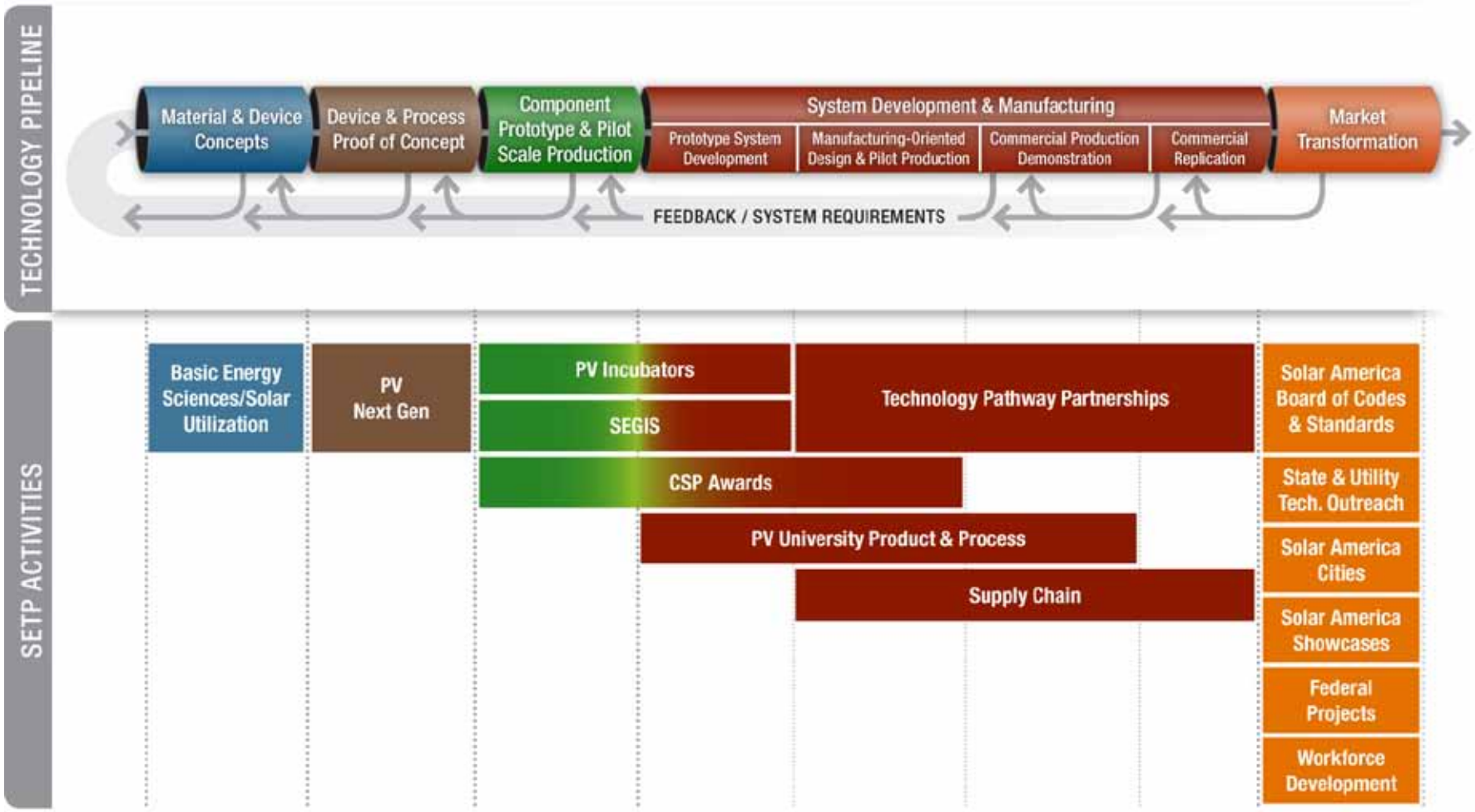
NREL and SNL provide a strong base for solar development partnerships with industry

- **Over 200 scientists and engineers with deep understanding of all solar technologies**
- **Areas of expertise**
  - Crystalline silicon and thin-film PV
  - Flat-plate and concentrator PV
  - Process development and engineering
  - System development and testing
  - Measurement and characterization
  - Reliability engineering
  - Next-generation PV technologies
  - CSP components and testing
  - Grid integration and power electronics

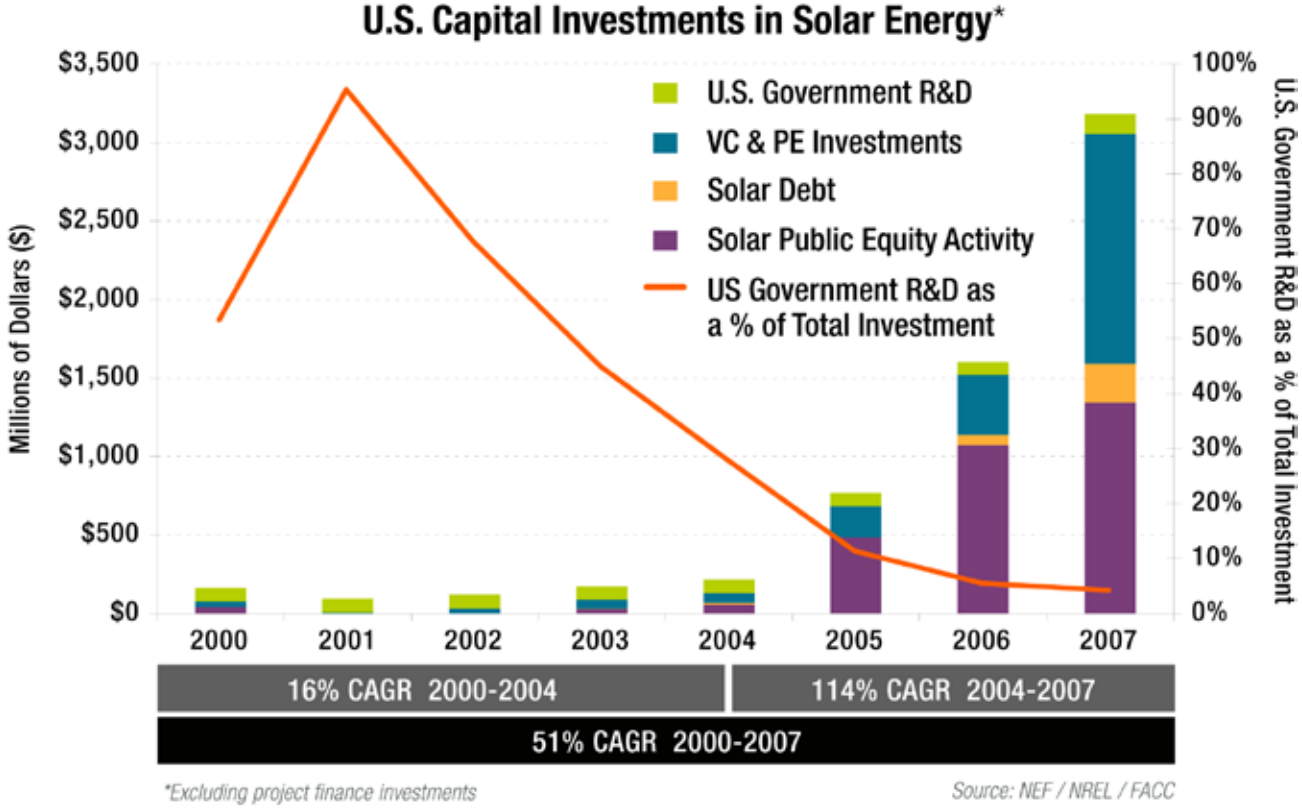
Collaboration Types
- Cooperative R&D Agreements (CRADA)
- Work-for-Others
- Technical Service Agreements
- Technology Licensing



DOE's Solar Energy Technologies Program (SETP) works along the whole RD&D pipeline



The SETP is a critical part of the total funding available for solar technologies



DOE Funding Advantages

1. Structured efforts with focus on full system costs (¢/kWh)
2. Preferential access to national labs
3. Fostering support for solar within large companies
4. Legitimizing young companies and new technology
5. Non-dilutive to company financing; minimal IP requirements

Challenges for Photovoltaics

- Continue to drive down costs and develop sufficient product diversity to address and maximize all market segments

- Ensure adequate supply chain for a large and rapidly growing industry

- Continue to provide reliable products with 30 yr lifetimes (both actual and perceived)

Challenges for Concentrating Solar Power

- Cost reductions and efficiency improvements must be achieved
  - Increase mirror reflectivity and durability
  - Increase receiver absorption
  - Identify lower freezing-point chemical solutions for heat storage
  - Increase heat storage beyond 7 hours
  - Grow the supply chain for advanced components
  - Develop innovative CSP systems for lower cost and operation in wider areas
- Identify the appropriate land areas for construction and ensure environmental impacts are minimized
- Develop a streamlined federal land application process

Technical Challenges for High-Penetration PV

- Ensure safe and reliable two-way electricity flow
- Develop smart grid interoperability
- Develop advanced communication and control functionalities of inverters
- Integrate renewable systems models into power system planning and operation tools
- Integrate with energy storage, load management, and demand response to enhance system flexibility
- Understand high-penetration limiting conditions
- Understand how various climates and cloud transients affect system reliability

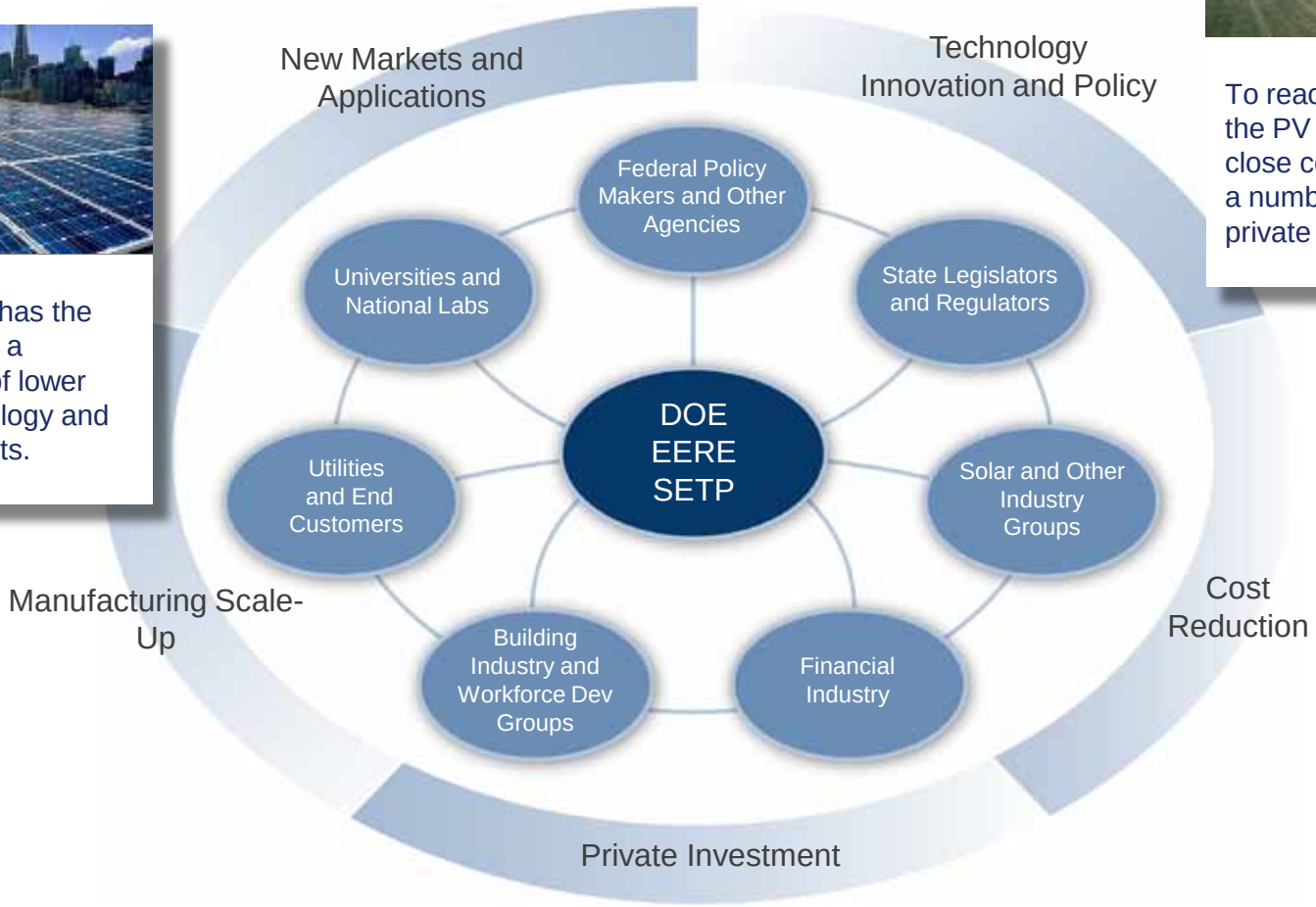
Challenges for Market Transformation

- Shortage of information about solar technologies and little consumer awareness
- Insufficient product standards
- Inconsistent interconnection, net metering, and utility rate structures and practices for solar systems
- Inadequate codes and complex and expensive permitting procedures
- Inconsistent and insufficient state and local financial incentives and other market drivers
- Lack of flexible, sophisticated, and proven financing mechanisms
- Limited education for and insufficient numbers of trained and experienced personnel and services

The SETP works with a number of stakeholders to grow and accelerate the U.S. the Solar Industry

The PV industry has the potential to enter a *"virtuous cycle"* of lower cost, new technology and expanded markets.

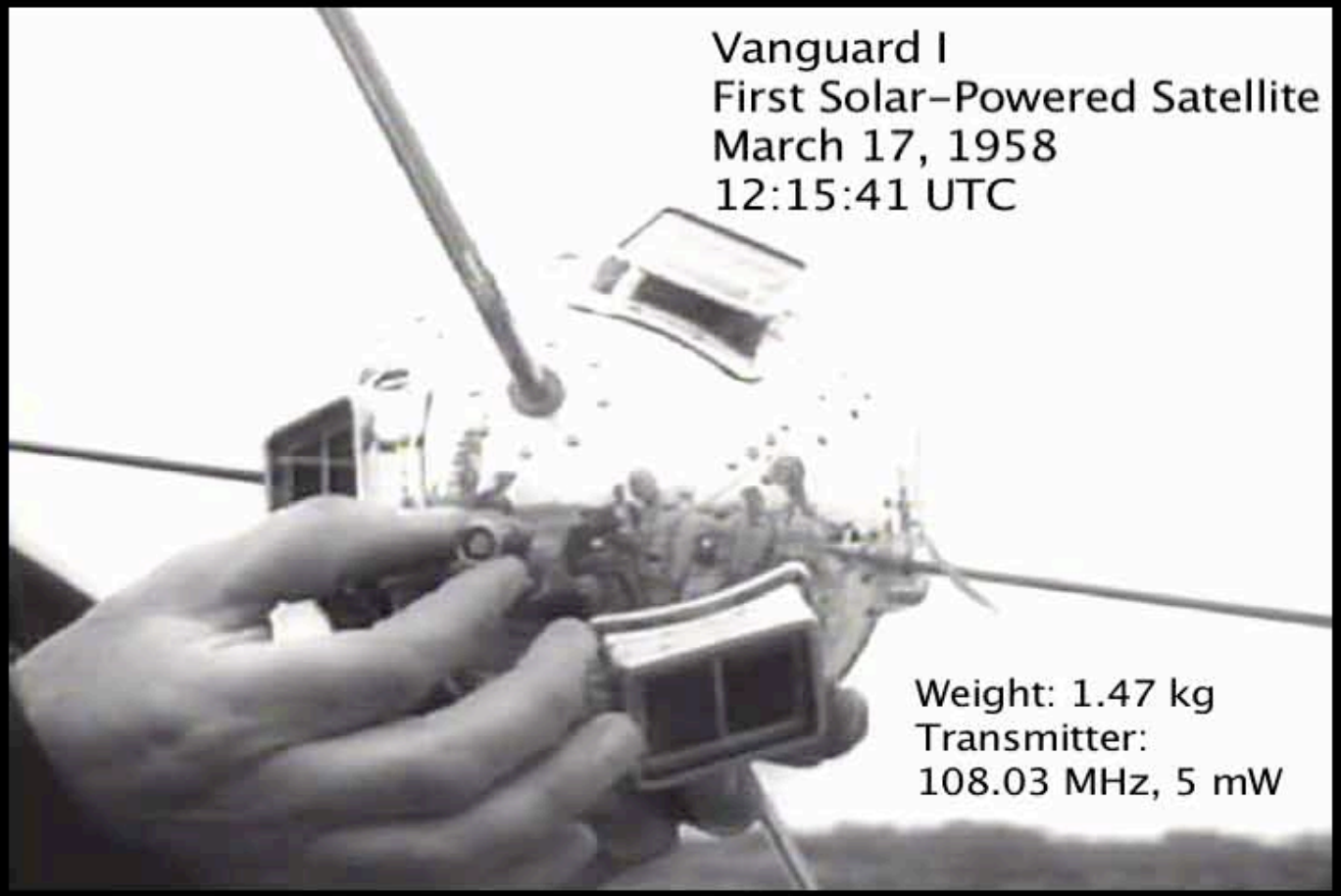
To reach it's full potential, the PV industry requires close coordination between a number of public and private entities.



Potential New Initiatives

- PV
  - BOS Reduction
  - BIPV
  - Next Gen
  - University Research
- CSP
  - Thermal Storage
  - Baseload/Higher Temp
  - Extended Geography
- Market Transformation
  - Colleges and Universities
  - Corporate Campuses
  - Showcases and Special Projects
- Grid Integration
  - Energy Storage
  - Large scale data collection and analysis
  - Industry Test and Evaluation Support
- Other
  - International outreach
  - Manufacturing base development
  - Workforce development
  - Next generation solar fuels
  - Demonstration Projects

(Gerald Pearson, Daryl Chapin, Calvin Fuller)


Vanguard I
First Solar-Powered Satellite
March 17, 1958
12:15:41 UTC
Weight: 1.47 kg
Transmitter:
108.03 MHz, 5 mW

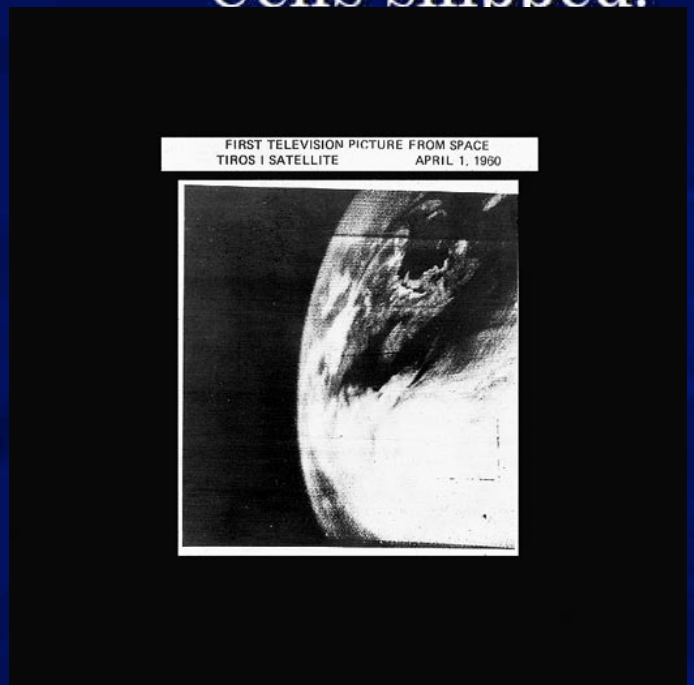
The Original Manufacturing Venture

The 1st player . . . Hoffman Electronics

(Power for a solar Vanguard)

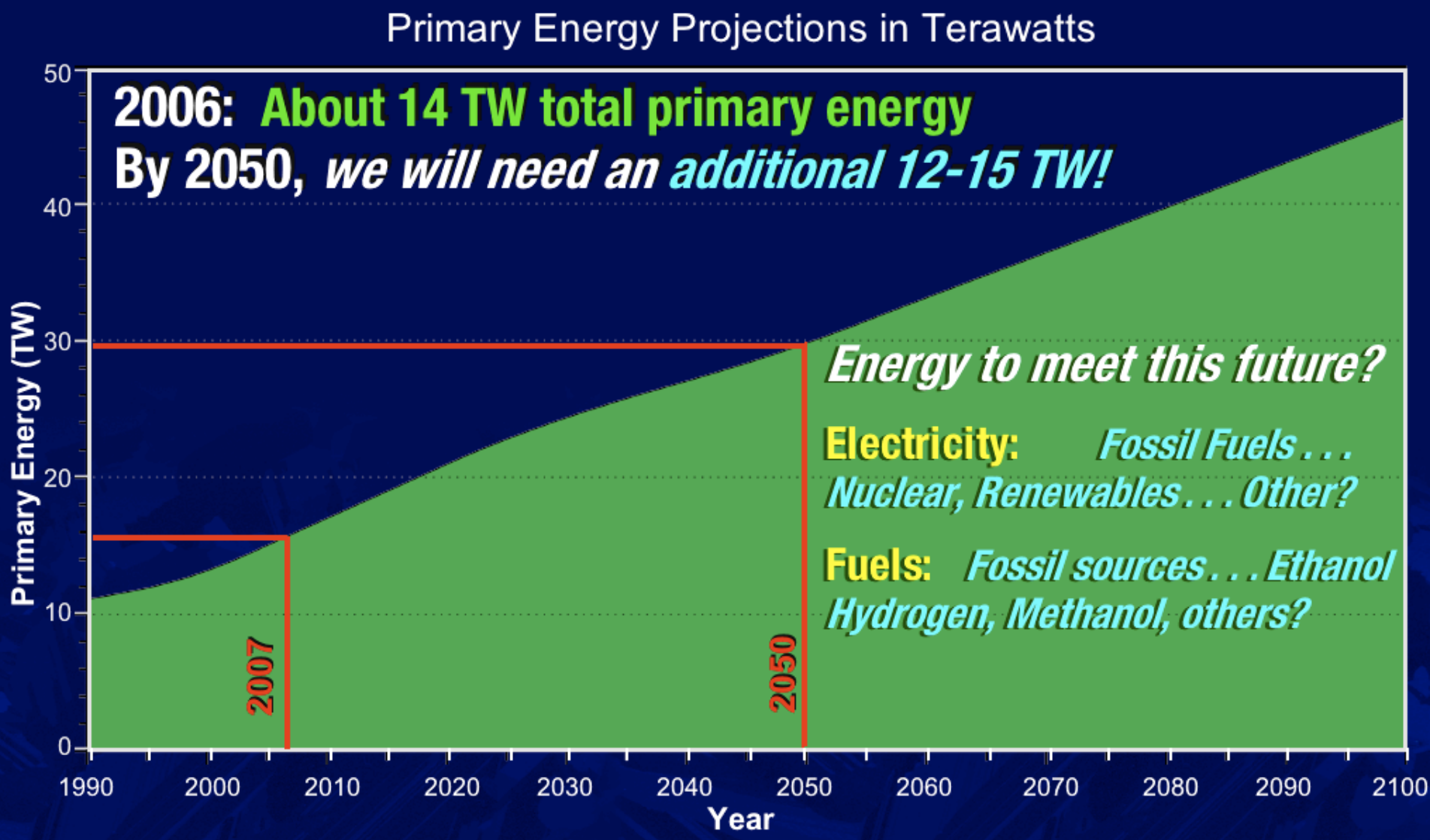
Hoffman Electronics (1958)

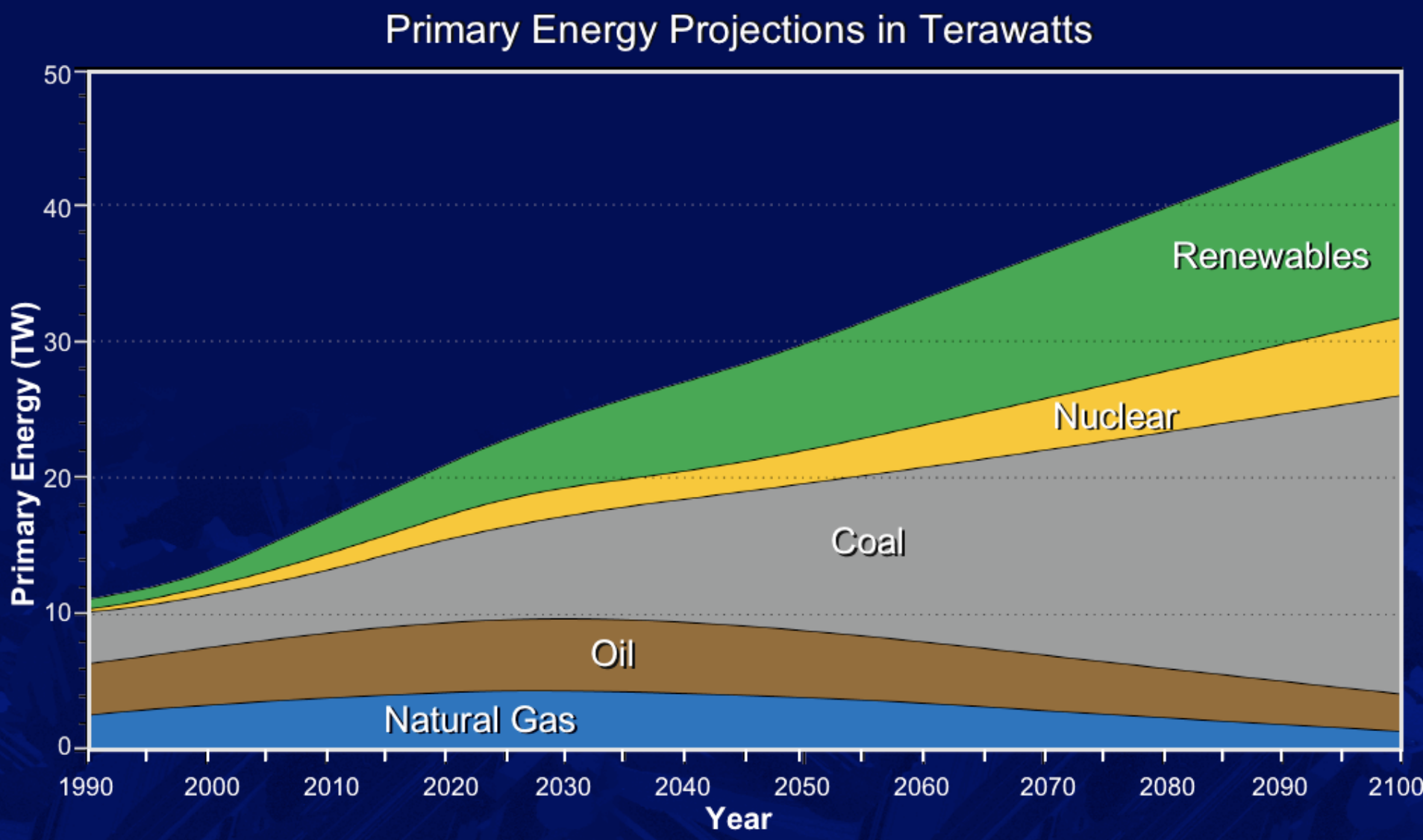
- Cell production capacity: *100s W*
- Cell production: *<50 W*
- Cells shipped: *~40W*



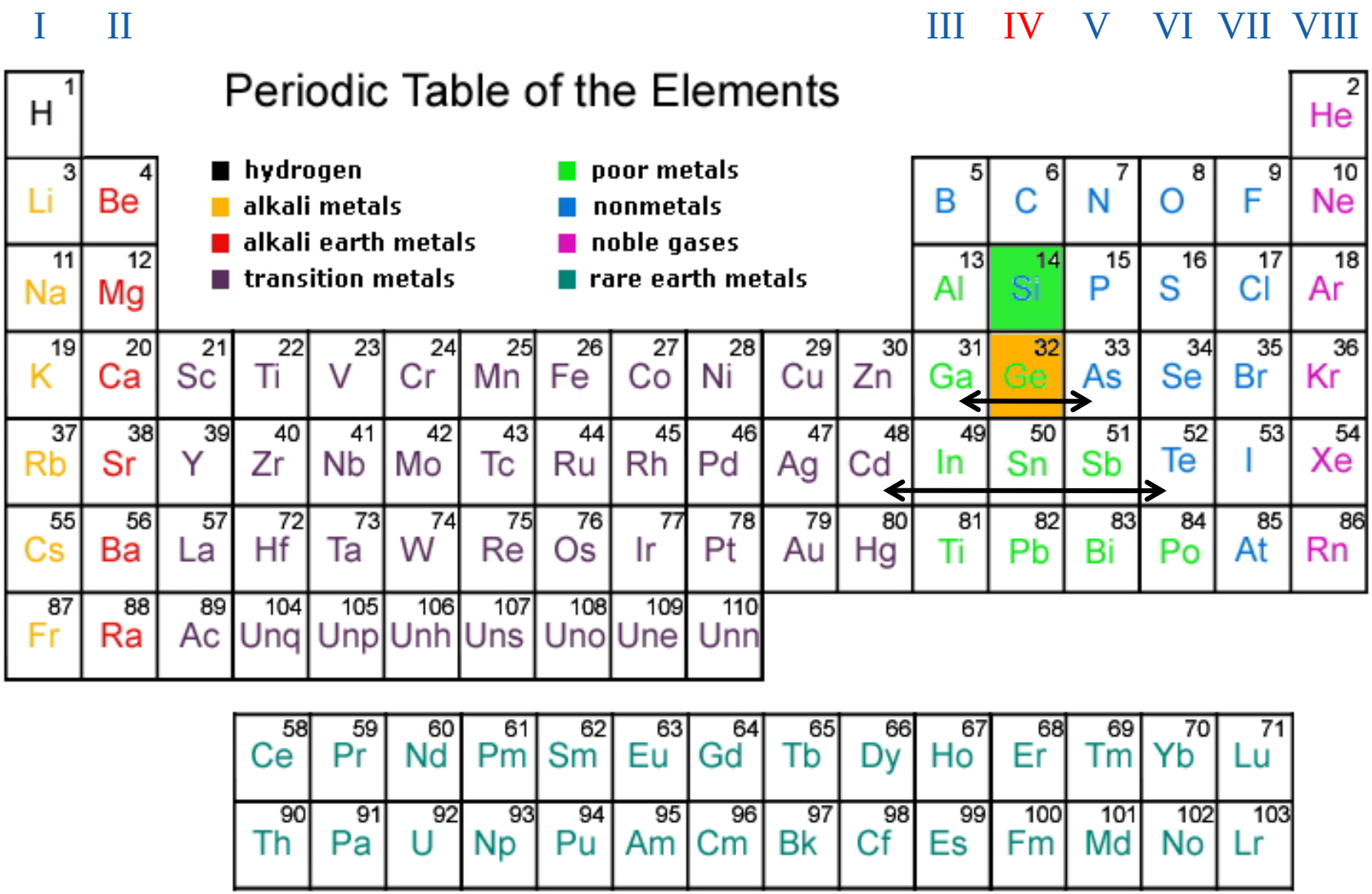
The Challenges *(The Terawatt Dilemma . . .)*

Worldwide Energy Consumption (now to the future):

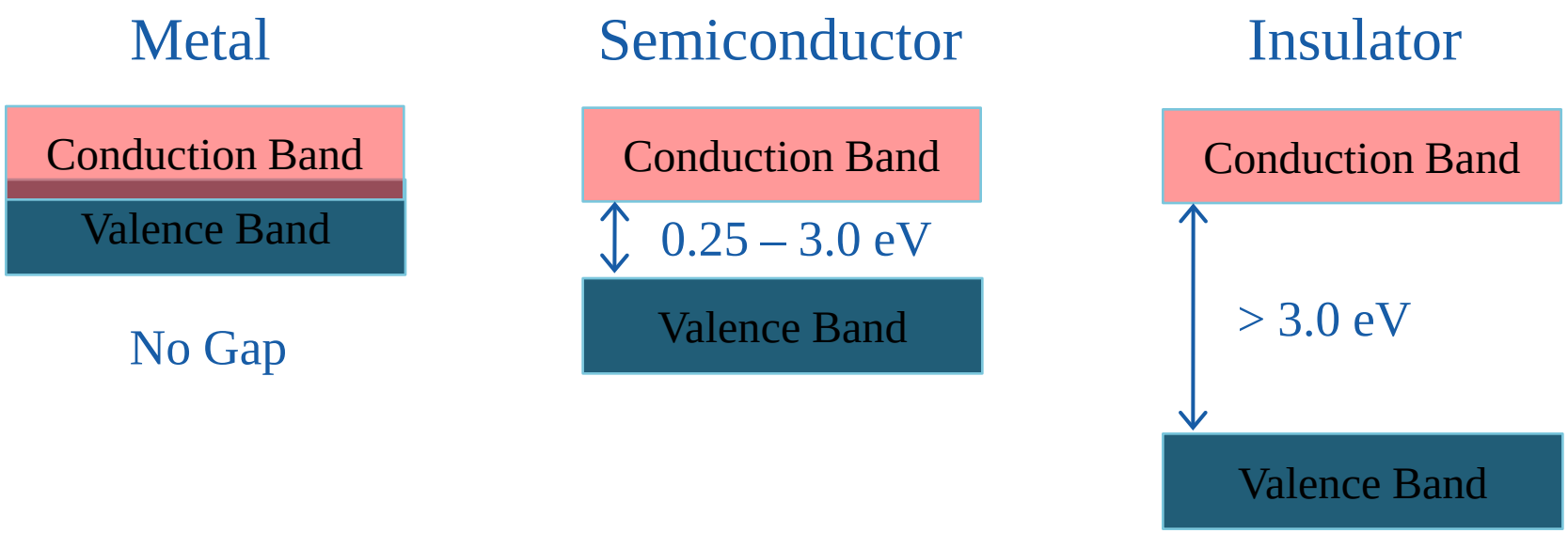


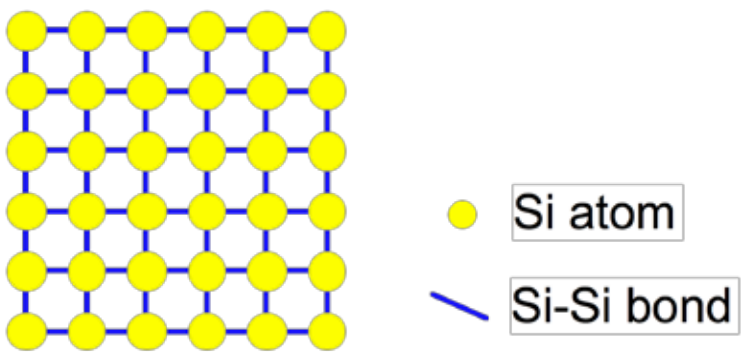

Primary Energy Projections in Terawatts
Primary Energy (TW)
50
40
30
20
10
0
Renewables
Nuclear
Coal
Oil
Natural Gas
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year

What is a Semiconductor?

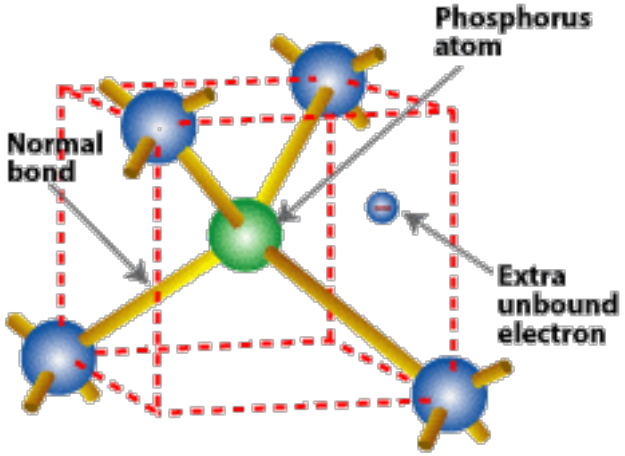


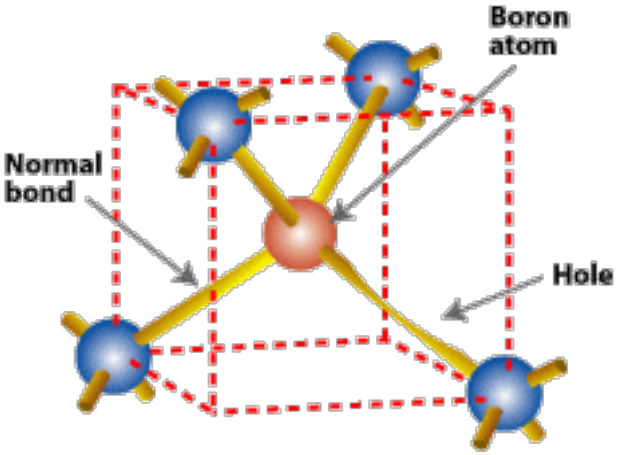
Between a Metal and an Insulator

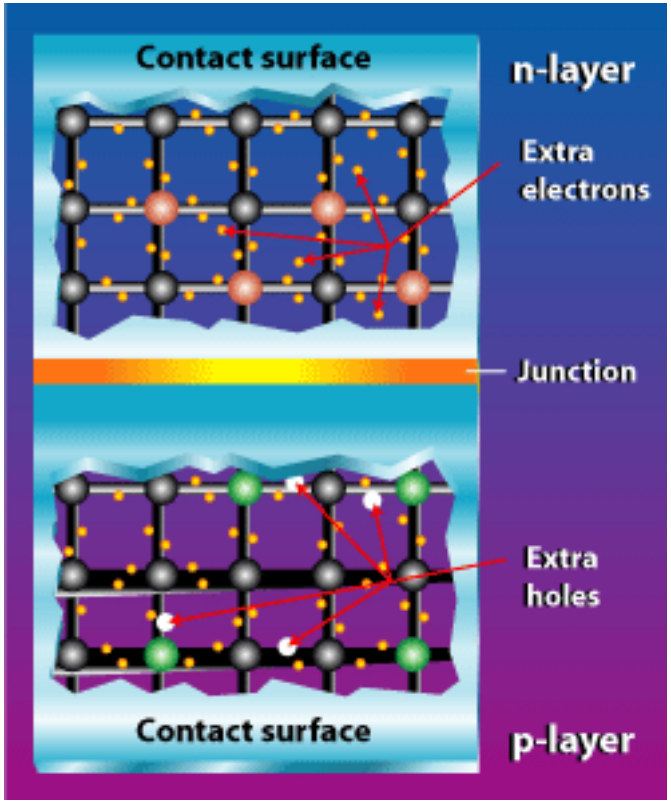




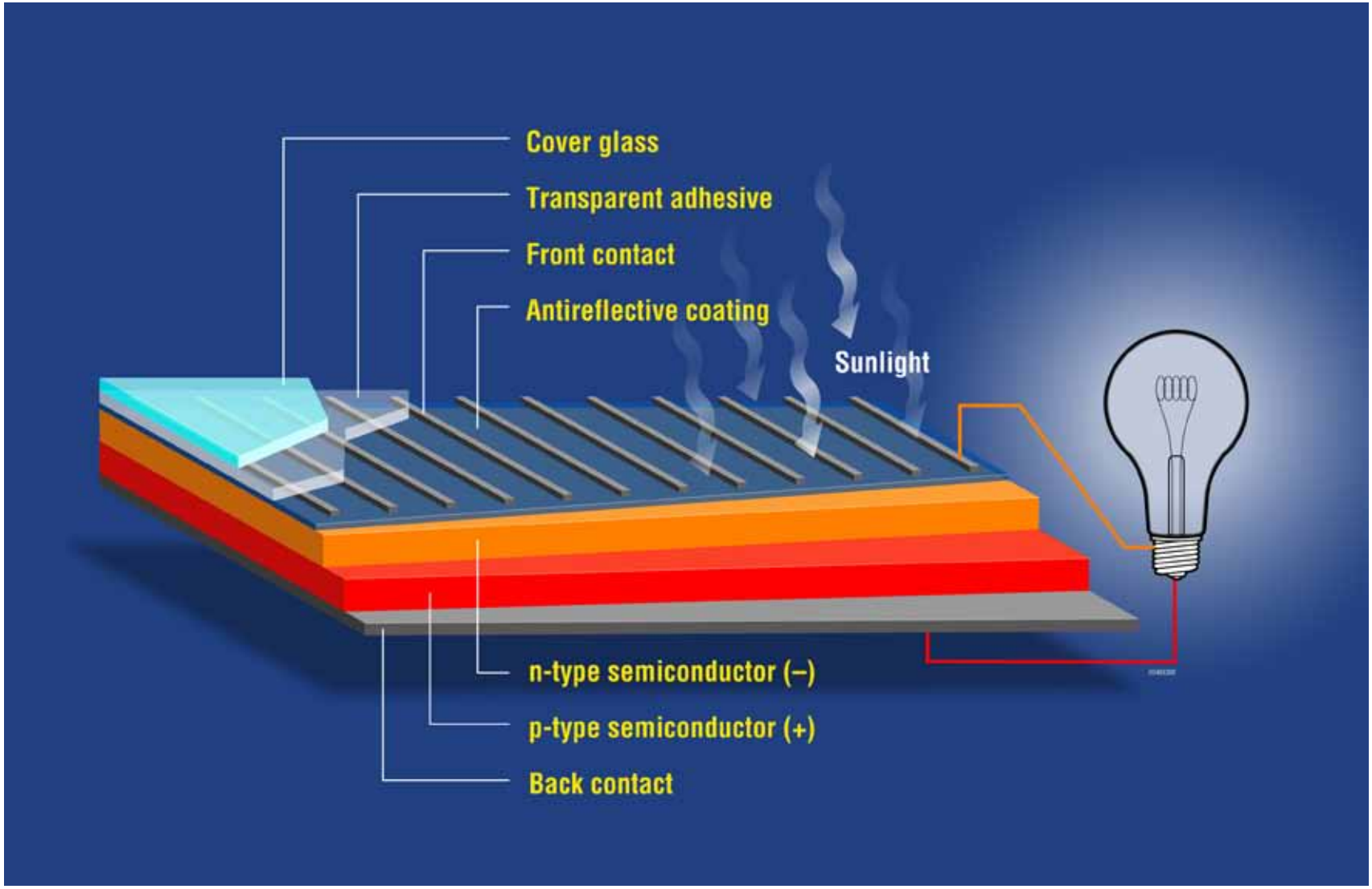
Making a p-n Junction



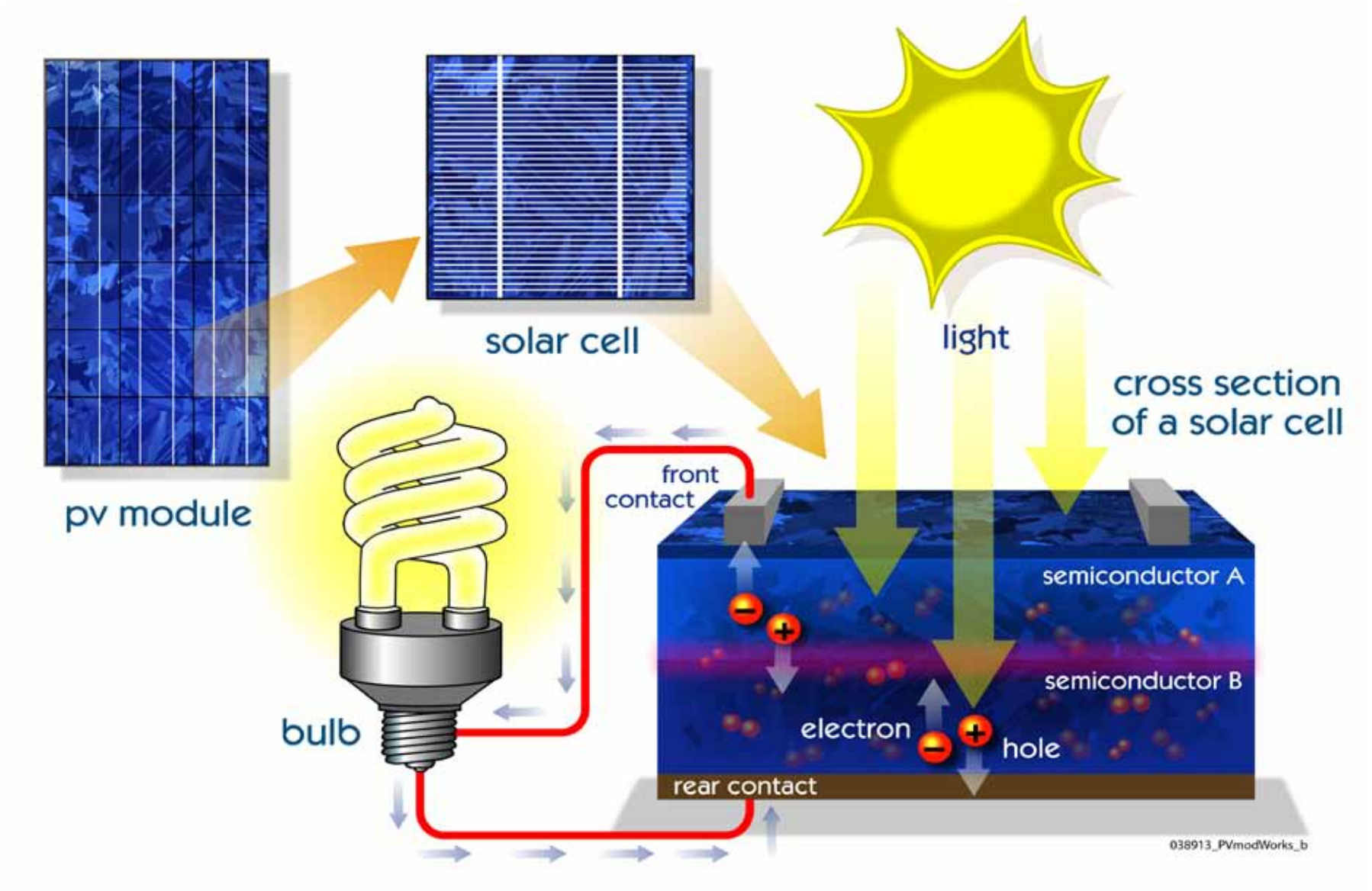




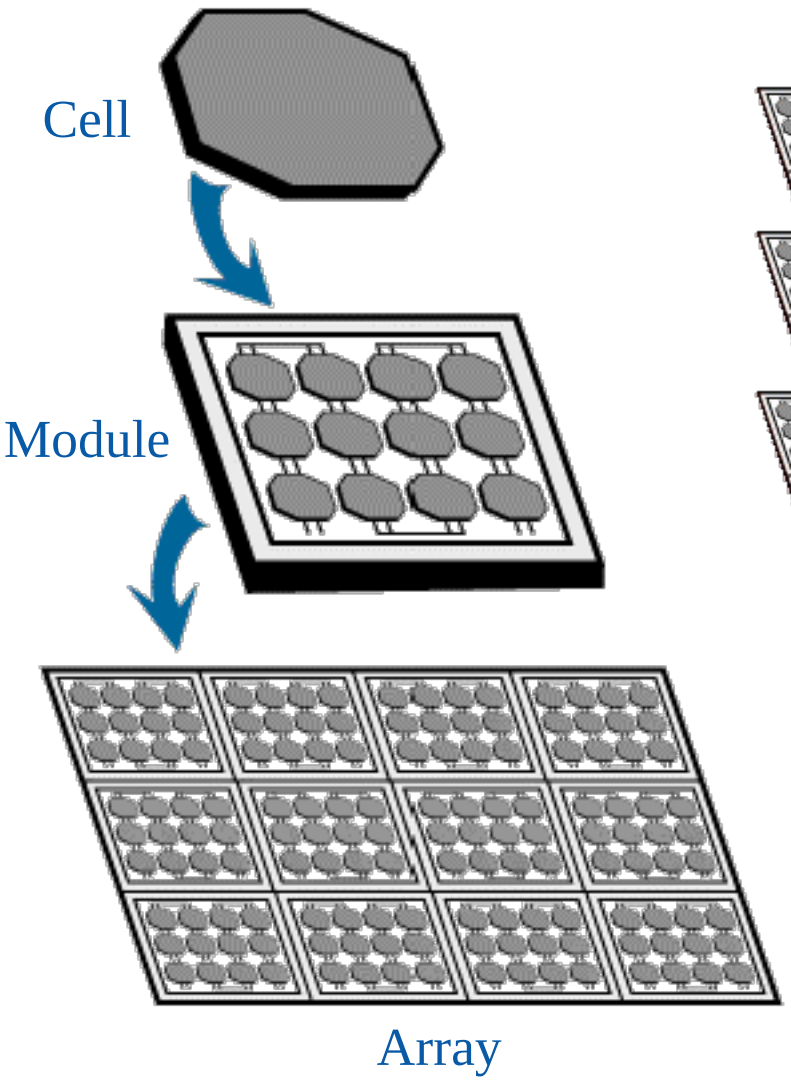
The Basic Solar Cell



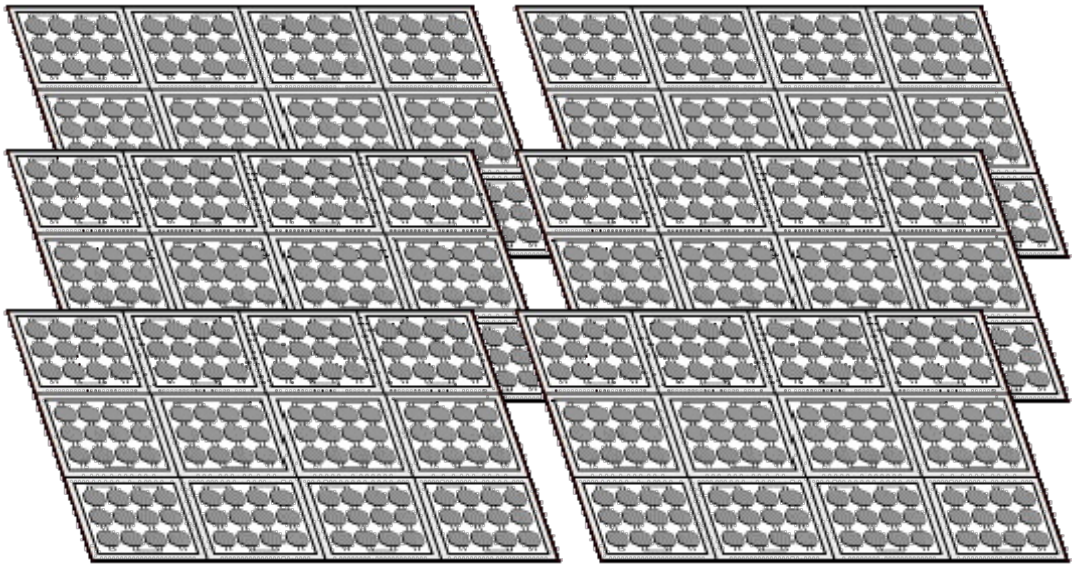
Solar Cell Operation

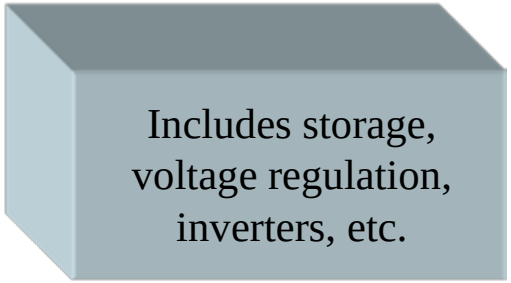


PV Systems Building Blocks



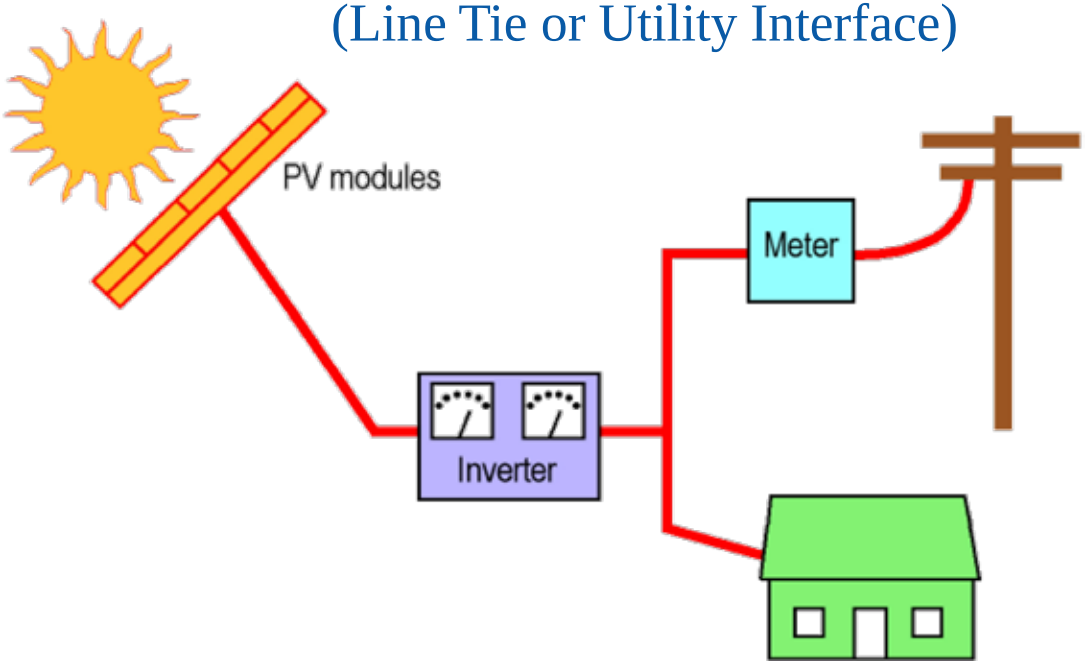
System



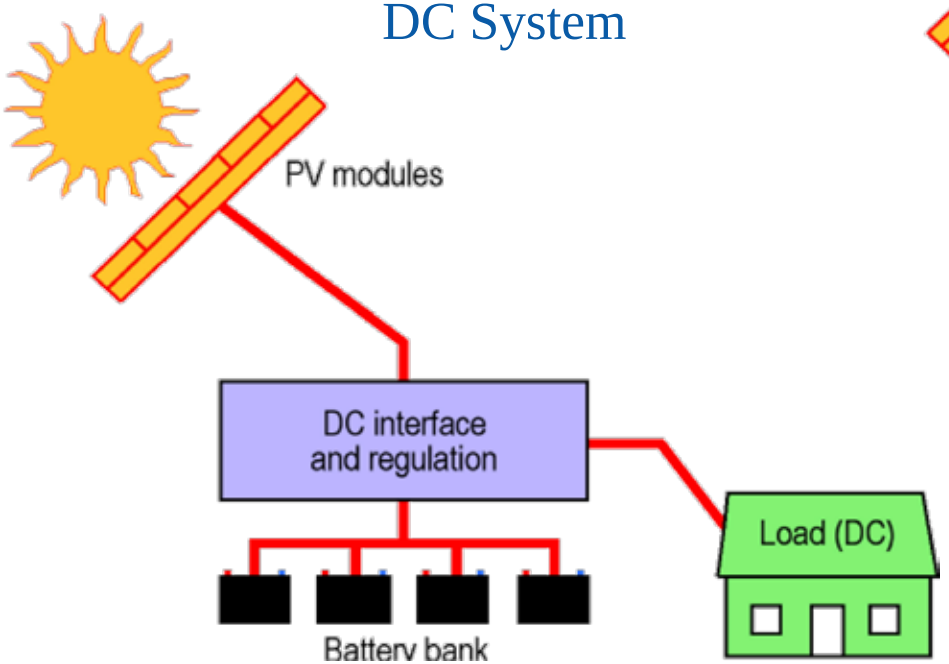


System Types

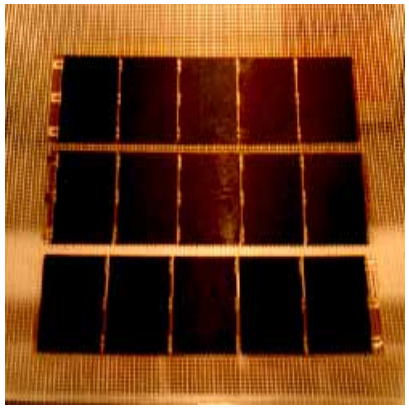
Grid Connected System
(Line Tie or Utility Interface)



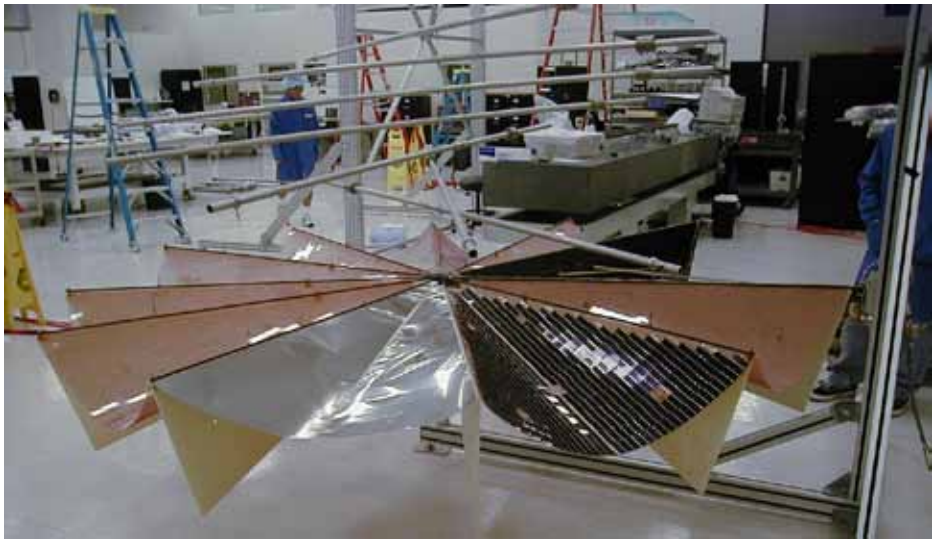
DC System



ARRAY TECHNOLOGIES



Thin Film Blankets
CIGS on polyimide



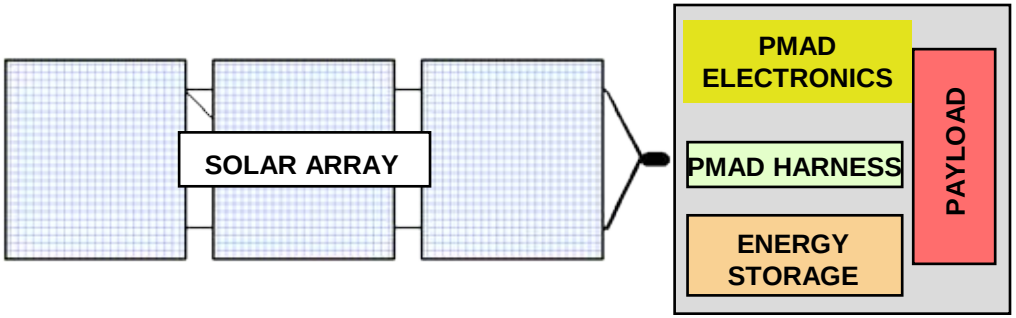
Flexible Array (Ultraflex)

Concentrator Arrays
(Stretched Lens Array)

Space Solar Power Systems

In present Earth-orbiting satellites ~ 20 - 35% of total mass and cost is the Electric Power System, the payload is ~ 23%

PMAD is Power Management and Distribution



- ↑ **Efficiency:** Drives area (A), mass (M), stowage volume (V), and cost

  Most important power system component (efficiency effects size and therefore mass)(cell type determines lifetime and also effects mass)

- ↓ **Size:** Drives launch vehicle, aerodynamic drag, radar cross-section, attitude control, and cost

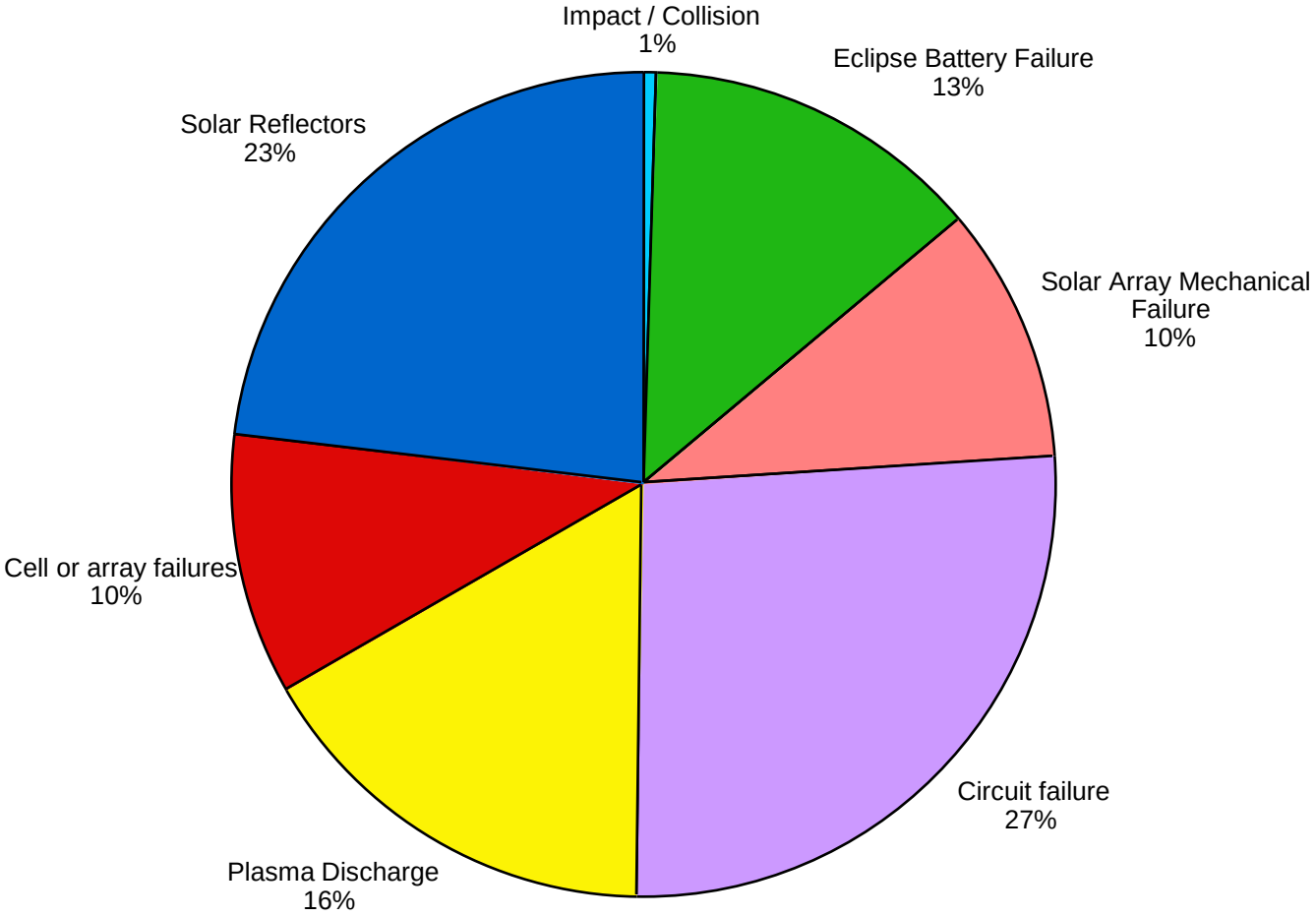
- ↓ **Mass:** Drives payload fraction, launch vehicle, and cost

- ↑ **Lifetime:** Drives mission availability, mission lifetime, and life cycle cost

Cost of Power-related Satellite Failures

Reported dollar value of loss due to power- related on-orbit failure 1990-2004 =

3.8 billion dollars



Data from 53 reported commercial and scientific satellite failures from 1990-23004
Does not include military, GPS, or reconnaissance satellites.

The Ultimate Goal: Competitive LCOE

Levelized Cost of Electricity (LCOE):

- Cost of an electricity-generating system over its lifetime
  - initial investment (capital) of entire system
  - operations and maintenance
  - fuel
- Costs are levelized in real dollars to present value.
- Minimum sale price for a project to break even.
- Defining the 'system boundaries' not always easy, e.g., grid expansion, environmental impacts, etc.

* Note that this does <u>not</u> include any environmental impact costs, i.e. carbon tax

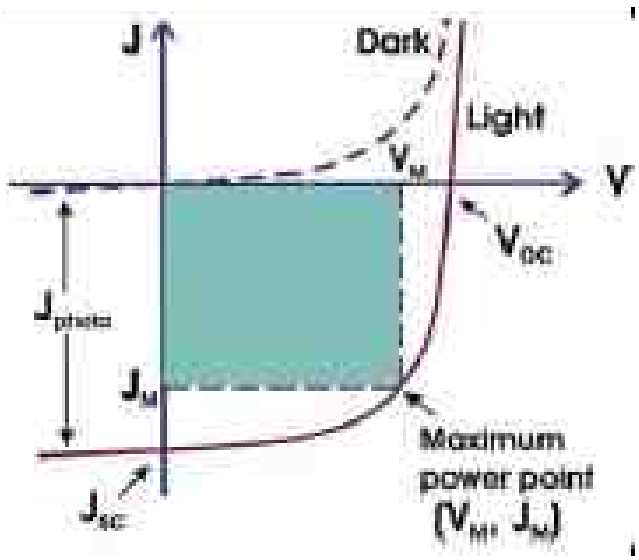
"The Big Three" LCOE drivers for PV modules

- Manufacturing Costs
- Efficiency
- Reliability

} Can be interrelated

The Cell “Gold Standards” JV & QE

Current-Voltage



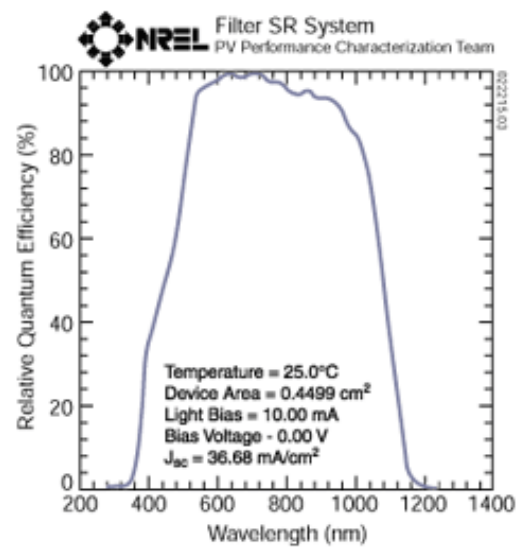
J-V measurement systems determine the electrical output performance of solar cells. This includes

- open-circuit voltage (Voc)
- short-circuit current (Isc)
- fill factor (FF)
- maximum power output (Pmax)
- voltage at maximum power (Vmax)
- current at maximum power (Imax)
- the conversion efficiency of the device (h).

Some I-V systems may also be used to perform dark I-V measurements to determine diode properties and series and shunt resistances.

Quantum Efficiency

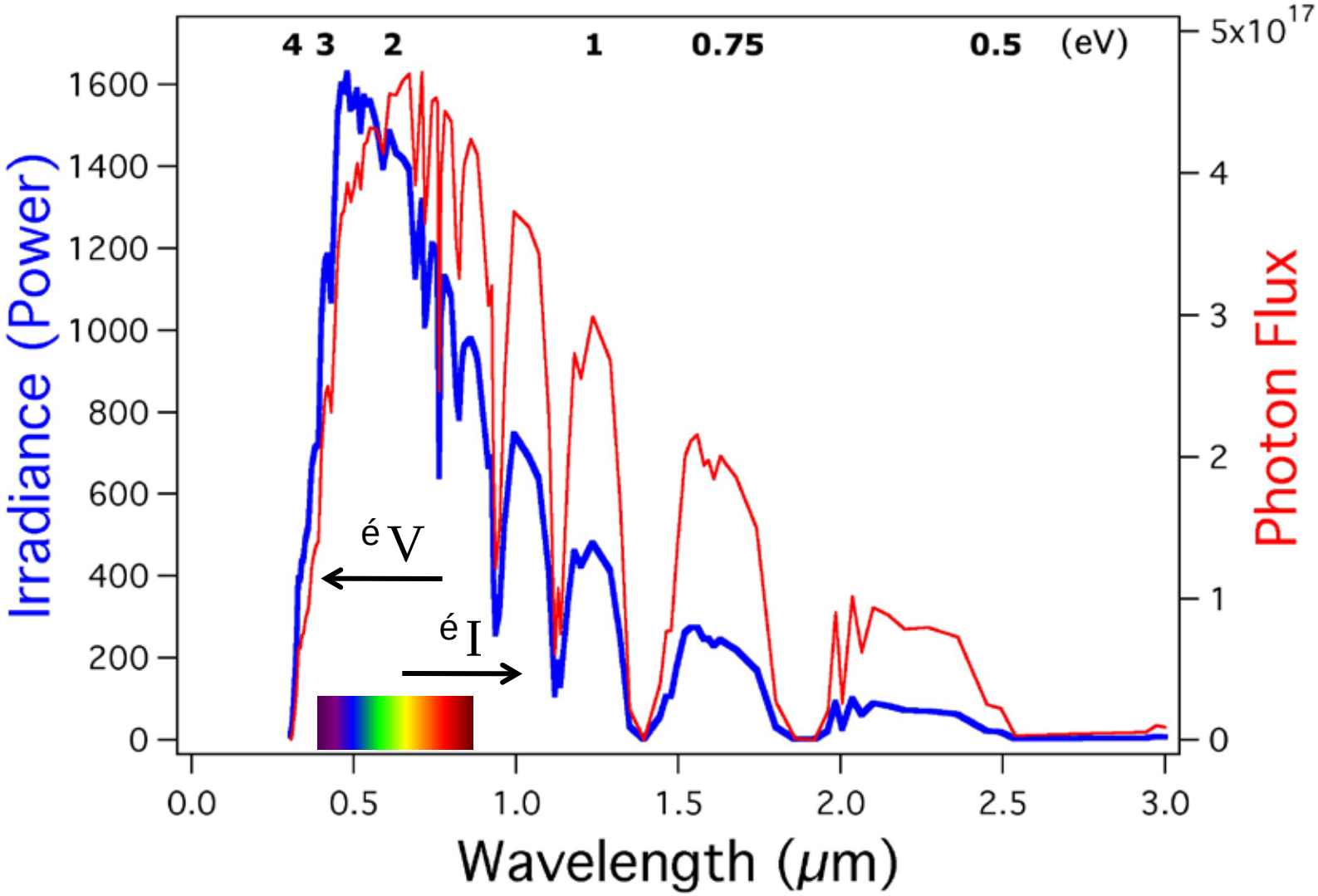
Spectral responsivity systems measure how a device responds to selected narrow (spectral) bands of irradiance. Responsivity is reported in terms of quantum efficiency (QE)—a measure of how efficiently a device converts incoming photons to charge carriers in an external circuit.



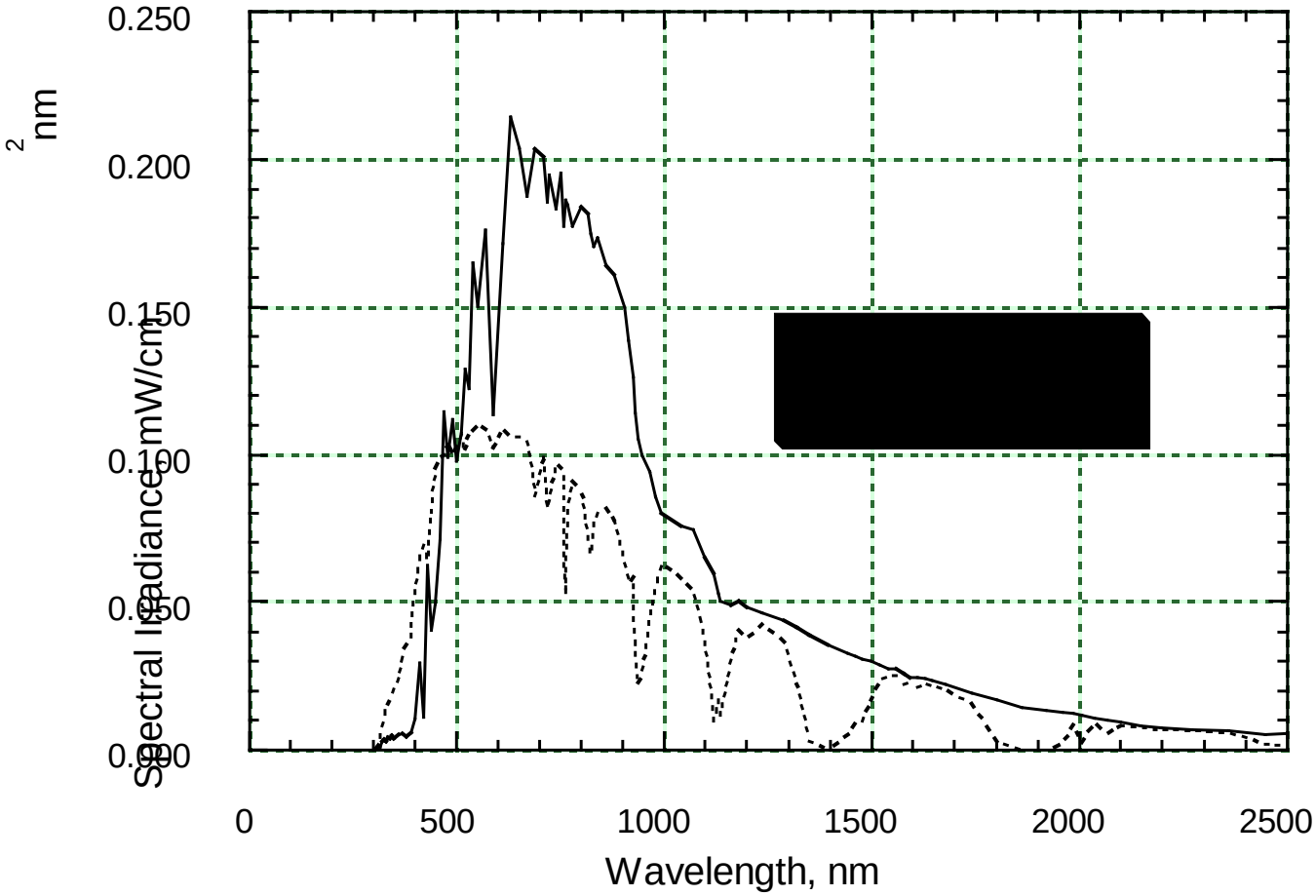
Typical output provided for spectral responsivity measurements for a high quality copper indium gallium diselenide device. Note, the quantum efficiency is high over almost the entire response range of the device.

Why so many PV technologies?

Part of the reason is the sun doesn't shine at one wavelength.



The Air Mass Zero (AM0) from the World Meteorological Organization (WMO) and Air Mass 1.5 spectrum



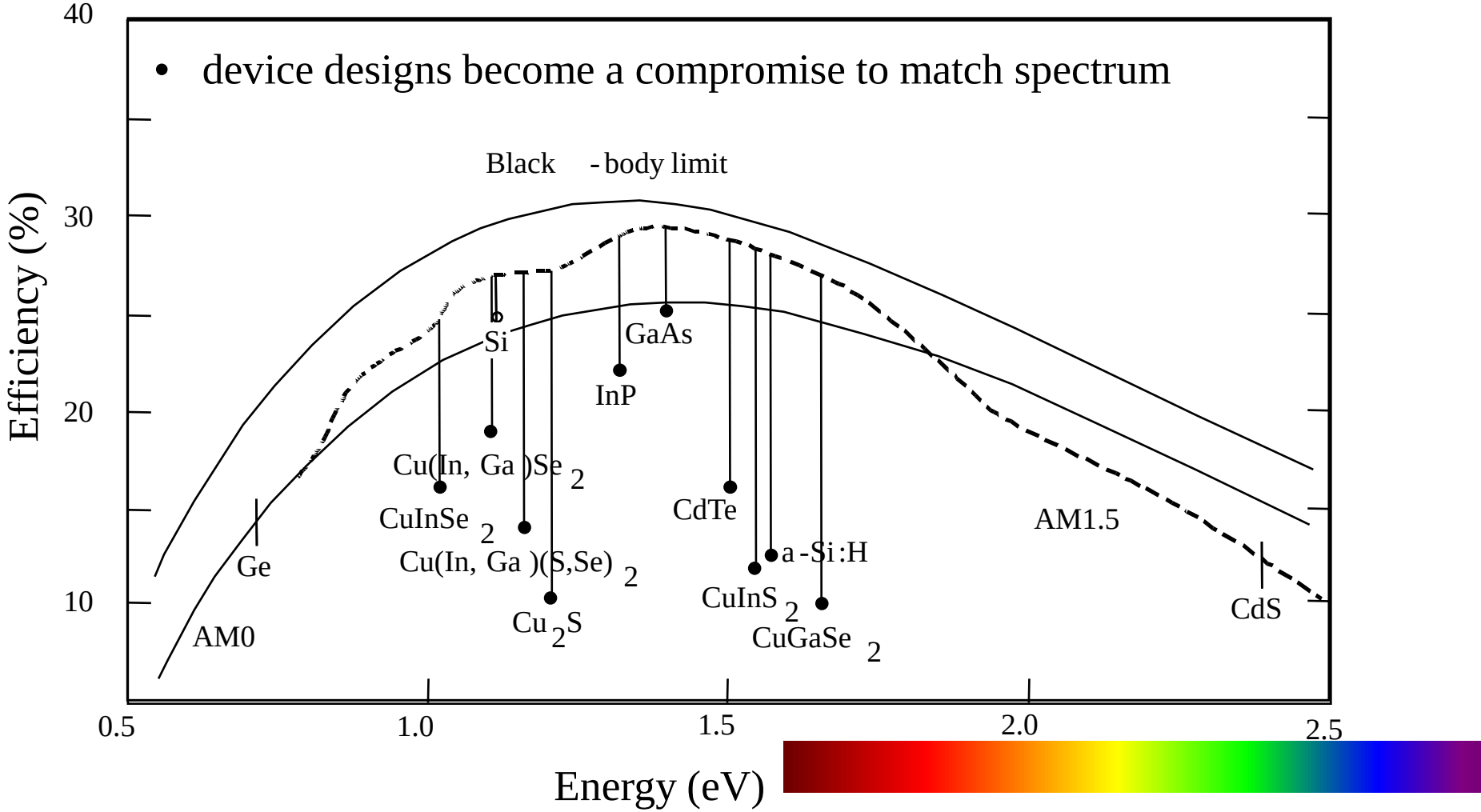
Confirmed terrestrial cell efficiencies[1] measured under global AM1.5 spectrum (1000W/m) at 25C The efficiency for global reference conditions was translated to AM0 using ASTM E-490-2000 (courtesy of Keith Emery)

Cells	Efficiency(%) Global AM1.5	Efficiency(%) AM0	Area (cm^2)	Manufacturer
c-Si	25.0	23.6	4	UNSW PERL
c-Si thin film transfer	16.7	14.8*	4.017	U.Stuttgart
GaAs	26.1	23.0*	.998	Radboud U. Nijmegen
GaAs (thin film)	26.1	23.0*	1.001	Radboud U. Nijmegen
InP	22.1	19.5*	4.02	Spire
GaInP/GaAs/Ge	32.0	30.2*	3.989	Spectrolab
GaInP/InGaAs/InGaAs		33.4	4.0	emcore
$Cu(Ga,In)Se_2$	19.4	16.9*	1.04	NREL
CdTe	16.7	15.0*	1.032	NREL
a-Si/a-Si/a-SiGe	12.1	10.8*	.27	USSC stablilised
Dye-sensitized	10.4	9.6*	1.004	Sharp
Organic polymer	5.15		1.021	Konarka
GaInP/GaAs/GaInAs	33.8	30.6	.0976	NREL, inverted monolithic

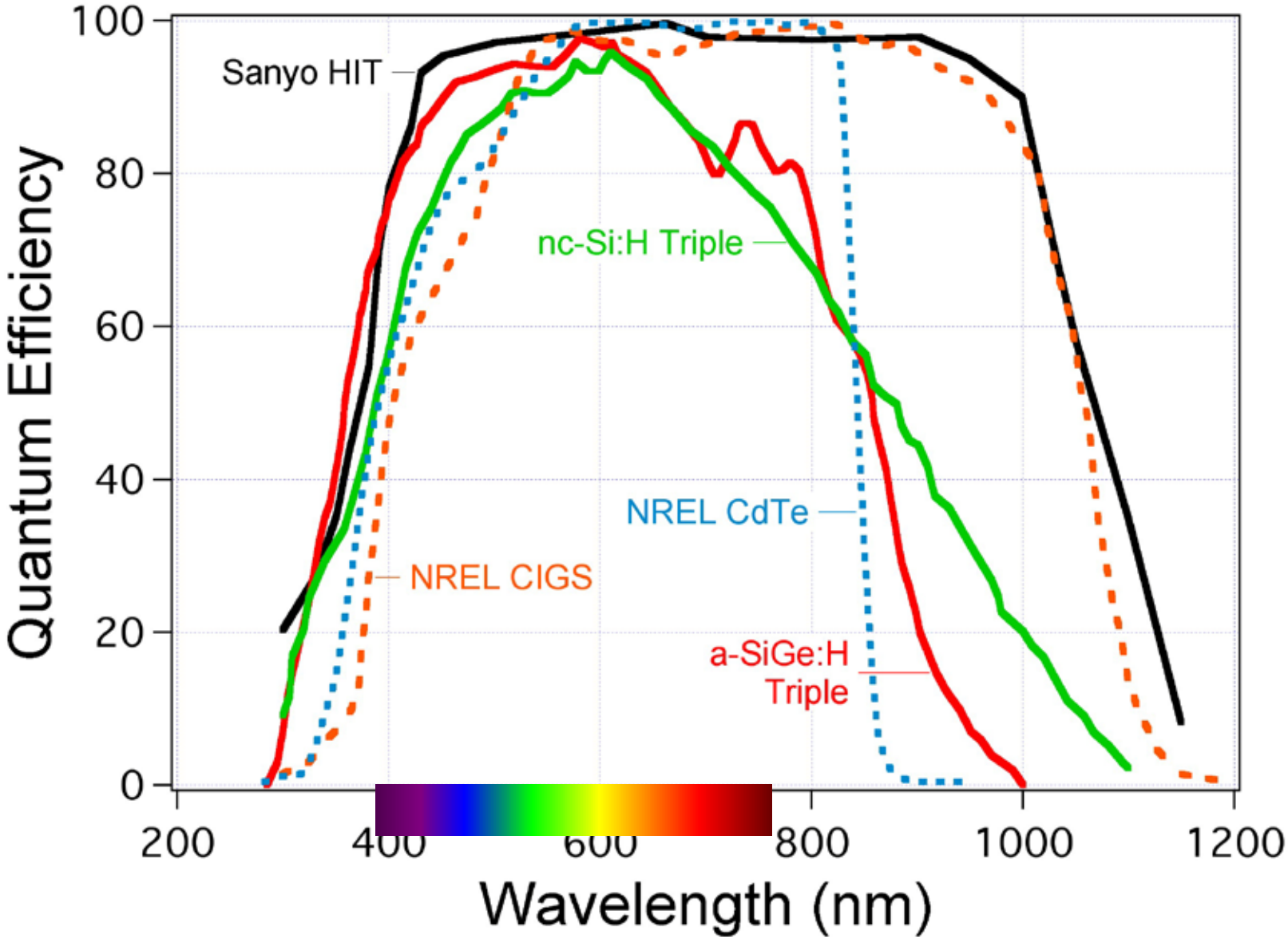
[1]Record efficiencies from Jan. 1, 2009 *Progress in Photovoltaics*

Material Bandgap Variability

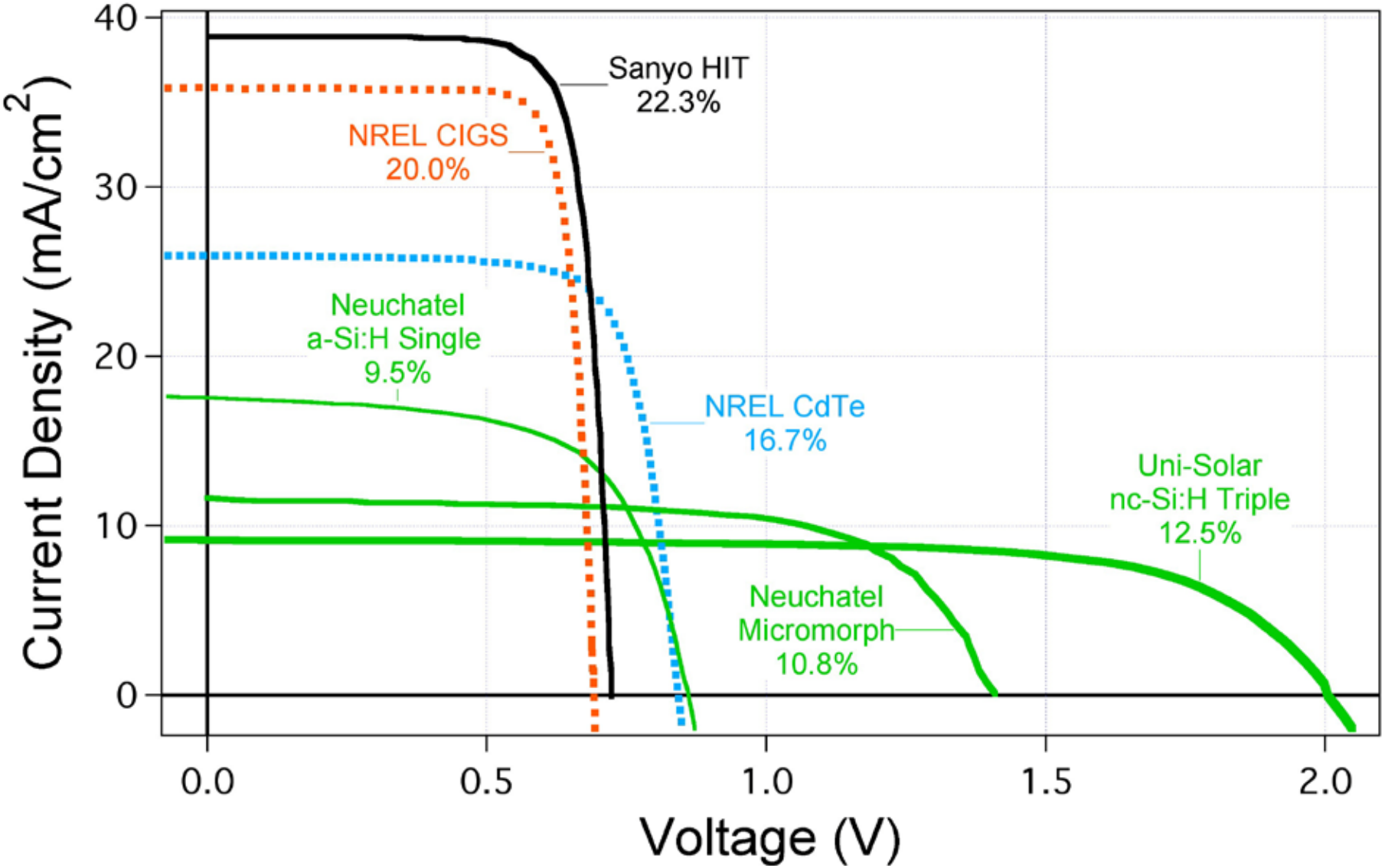
- no perfect material to match the spectrum
- device designs become a compromise to match spectrum



Best of Kind QE's



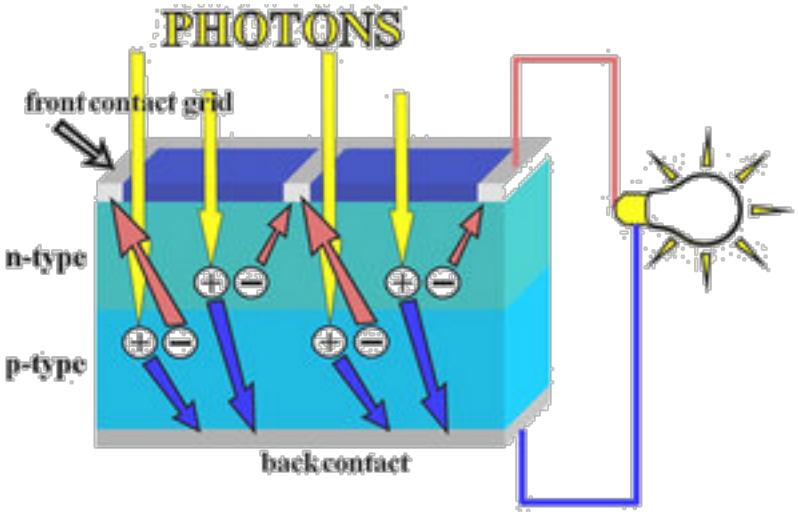
Best of Kind JV's



Converting the sun's radiation into electricity – two main pathways

Photovoltaics (PV)

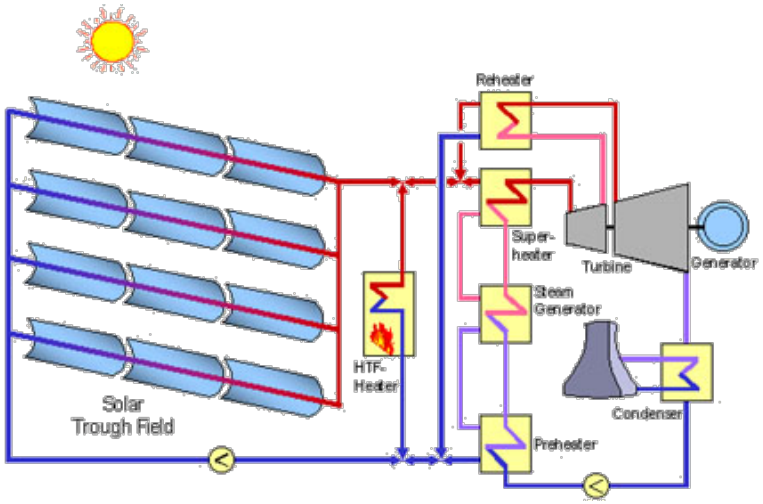
Cells of semi-conductors absorb photons and directly convert them into electrical current.



Can be used anywhere in the U.S.

Concentrating Solar Power (CSP)

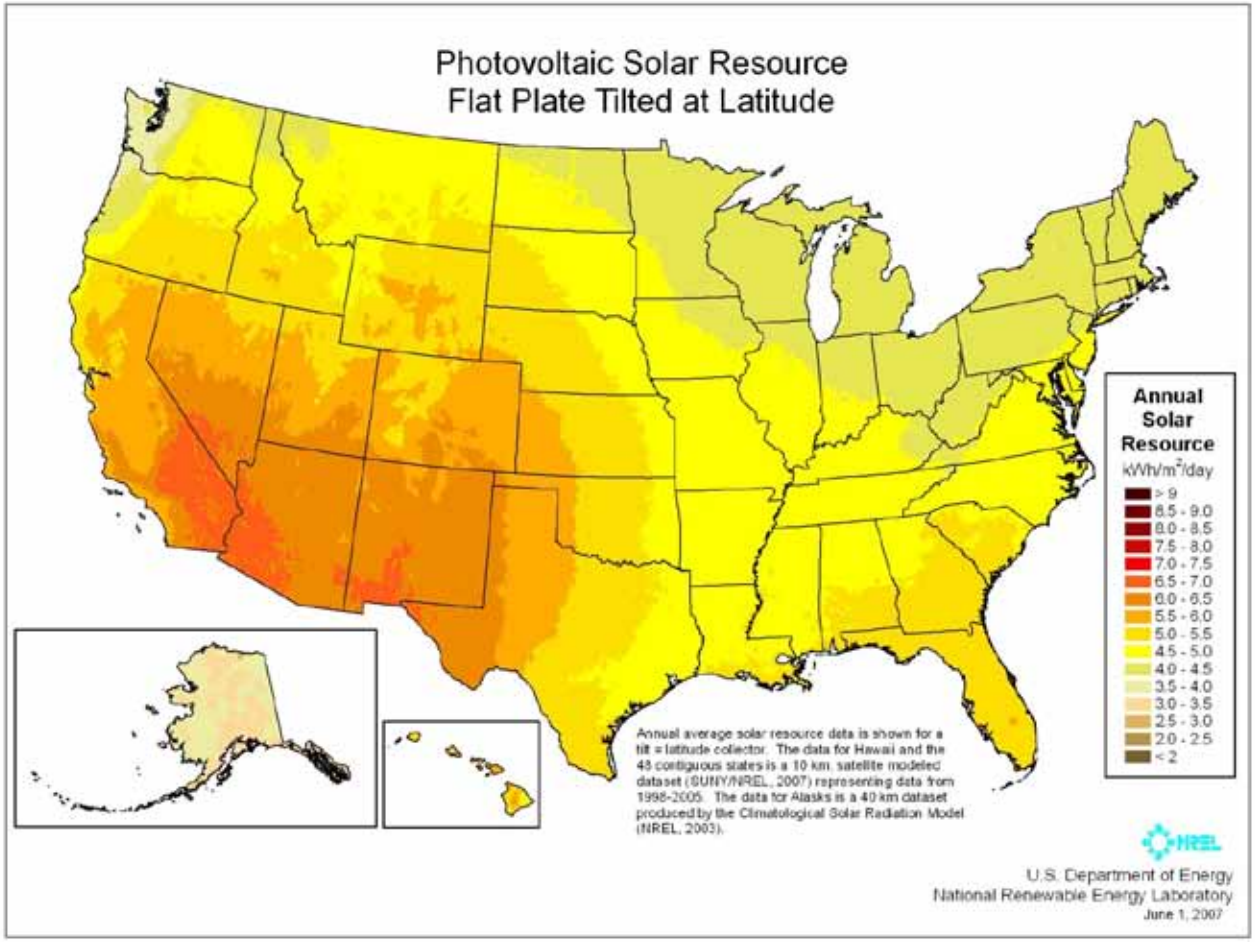
Mirrors focus solar radiation to heat fluids that are used to drive electric generators.



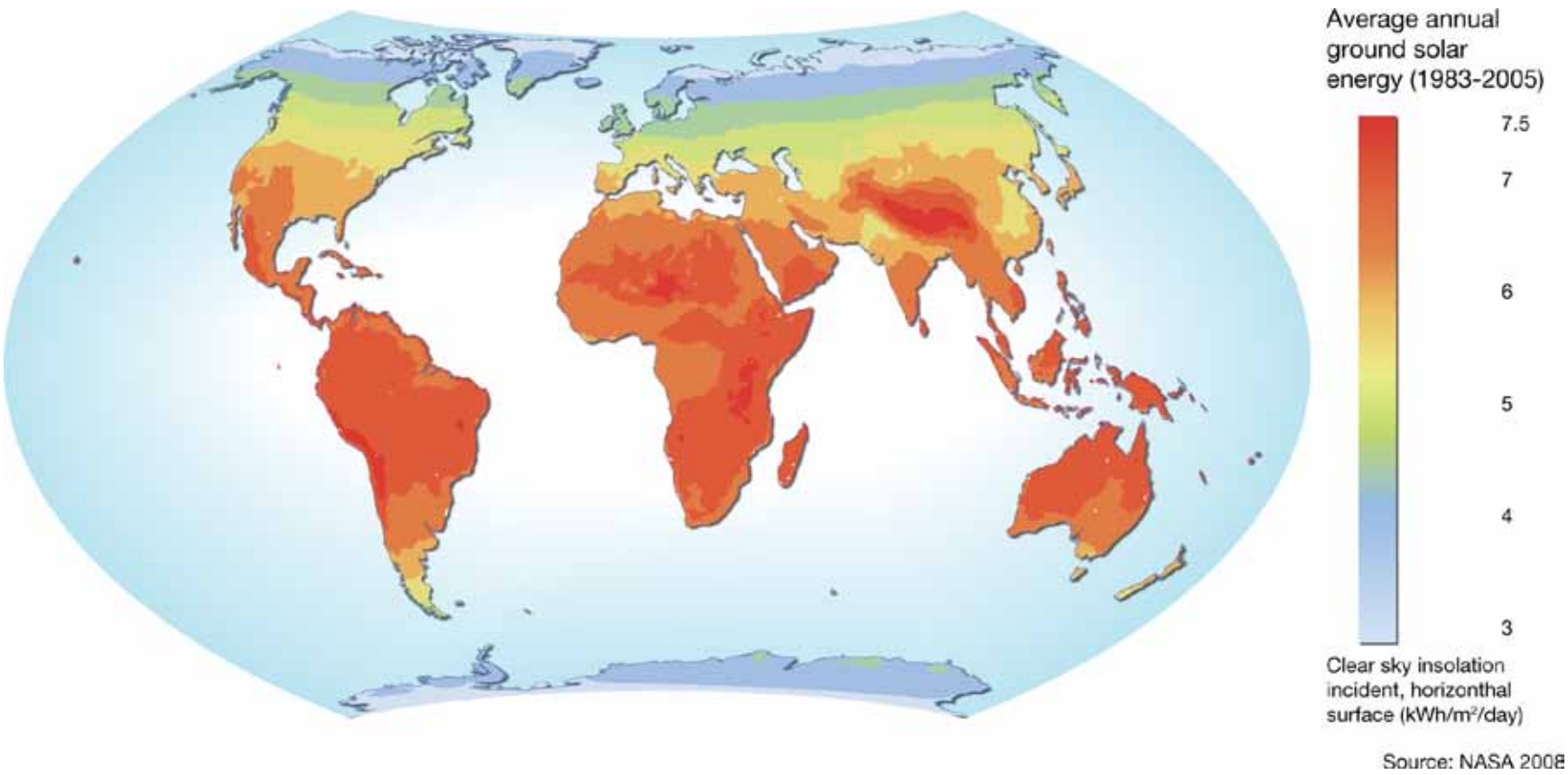
Predominantly in the Southwest U.S. (requires direct sunlight)

In the U.S. solar resources significantly outweigh energy use

- Currently, solar provides less than 0.1% of the electricity used in the U.S.
- For the U.S., less than 2% of the land dedicated to cropland and grazing could provide all of our electricity.

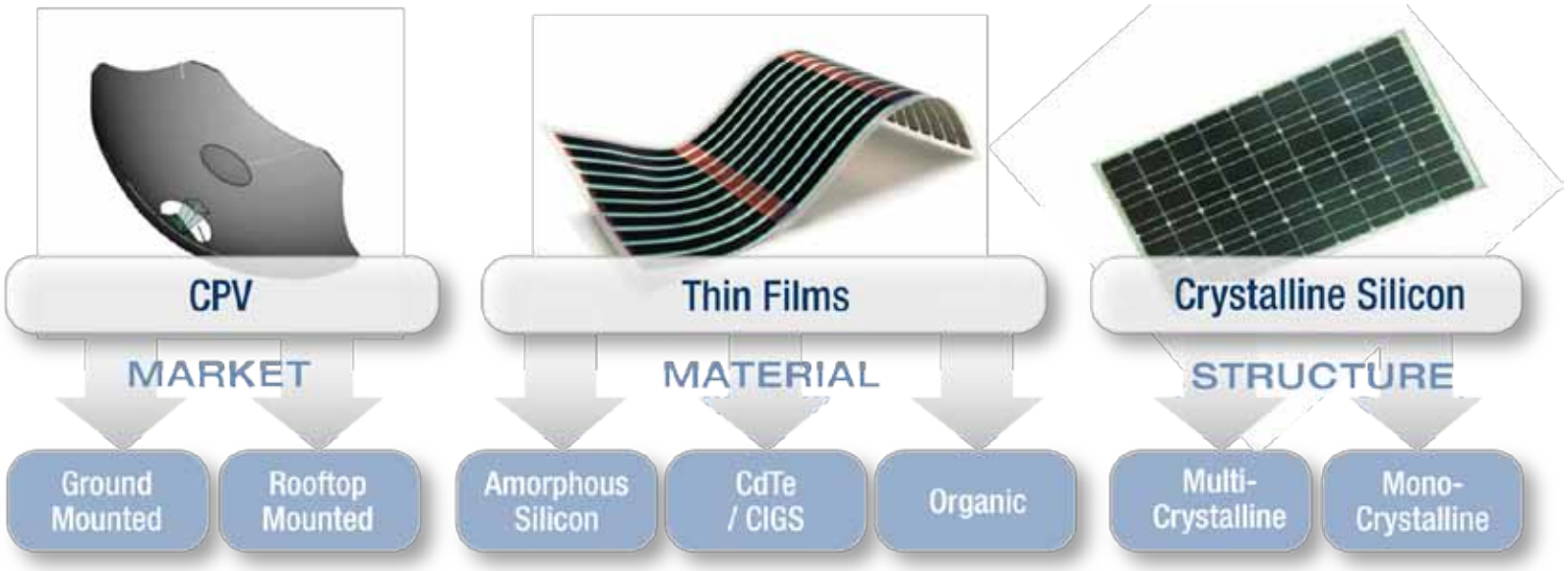


Also globally solar resources significantly outweigh energy use



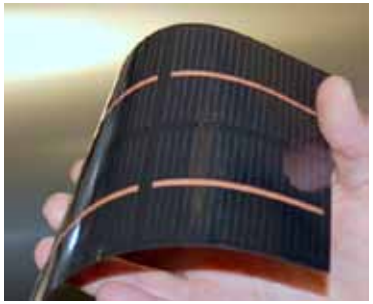
- Covering less than 0.2% of the land on the earth with 10%-efficient solar cells would provide twice the power used by the world.

Government and industry are pursuing a range of promising PV technologies…

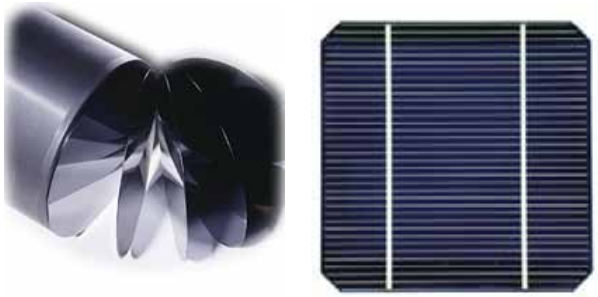


20x-100x

500x



$Cu(In,Ga)Se_2$ ~ 1-2 um



c-Si ~ 180 um

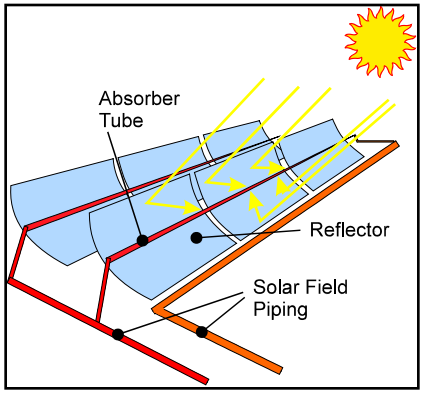
… and a range of promising Concentrating Solar Power (CSP) technologies

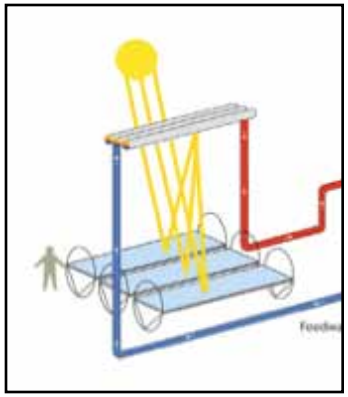
Trough

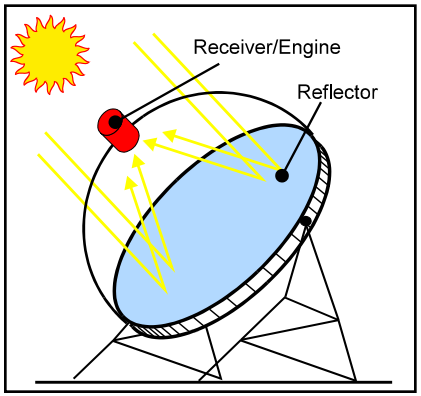
Linear Fresnel

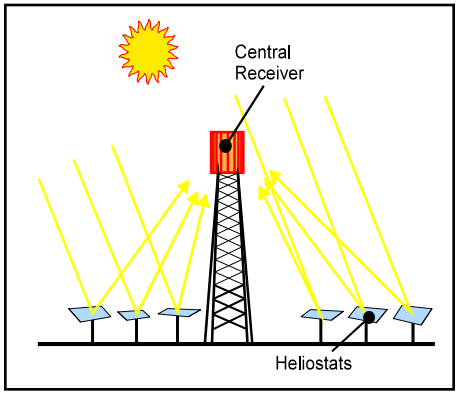
Dishes

Tower









Utility scale power plants – intermediate and base load power

Both PV and CSP applications and markets are evolving very rapidly

Residential

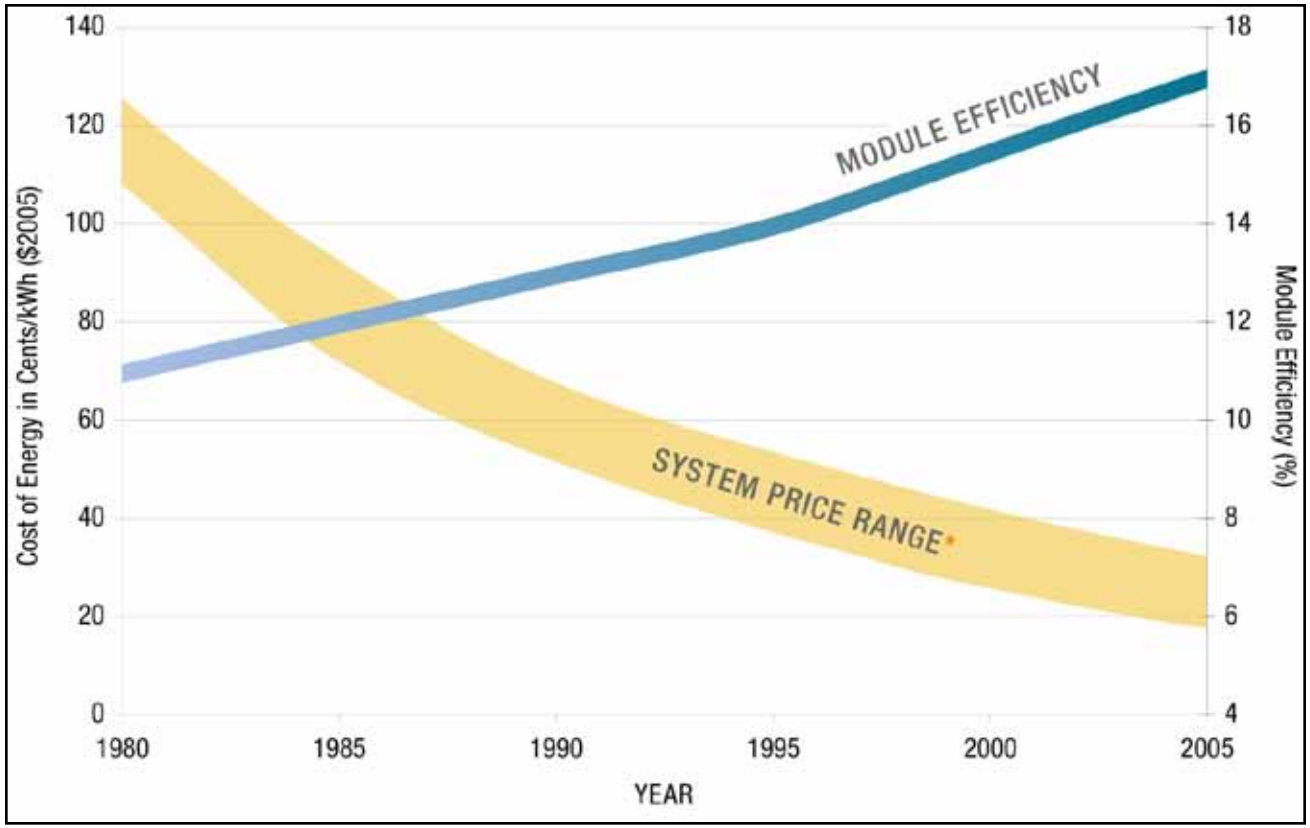
- Solar is a growing source for distributed & centralized electricity generation

Commercial

Utility-scale

Dramatic reduction in cost and increase in efficiency of PV over past 25 years

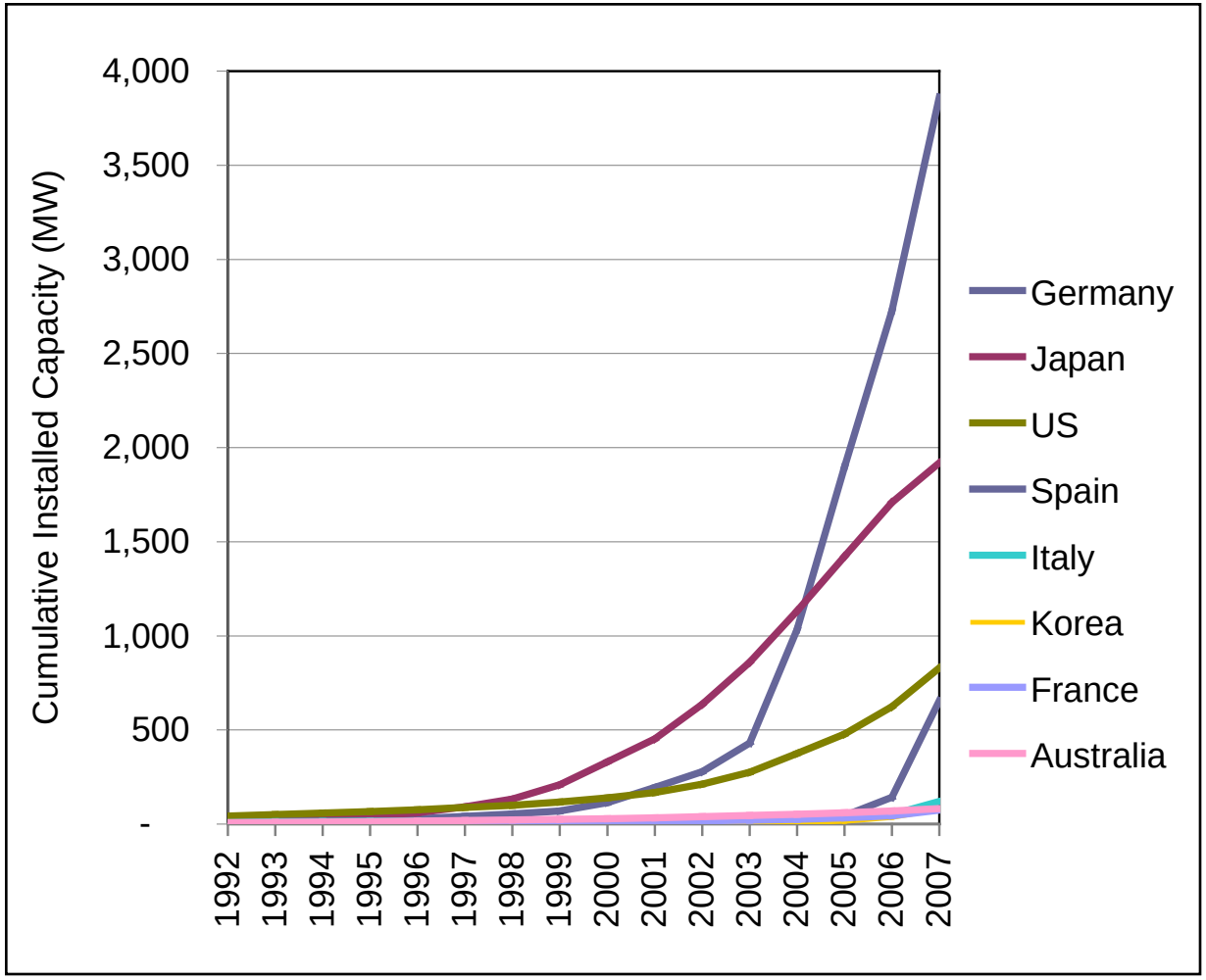
Historical PV Cost Curve (Silicon-based Technologies)



* System price is dependent upon location, application and variable financing options.
Source: NREL.

- Government investment in solar R&D has had a significant impact.
- System prices must come down another 50-70% to achieve grid-parity nationwide.

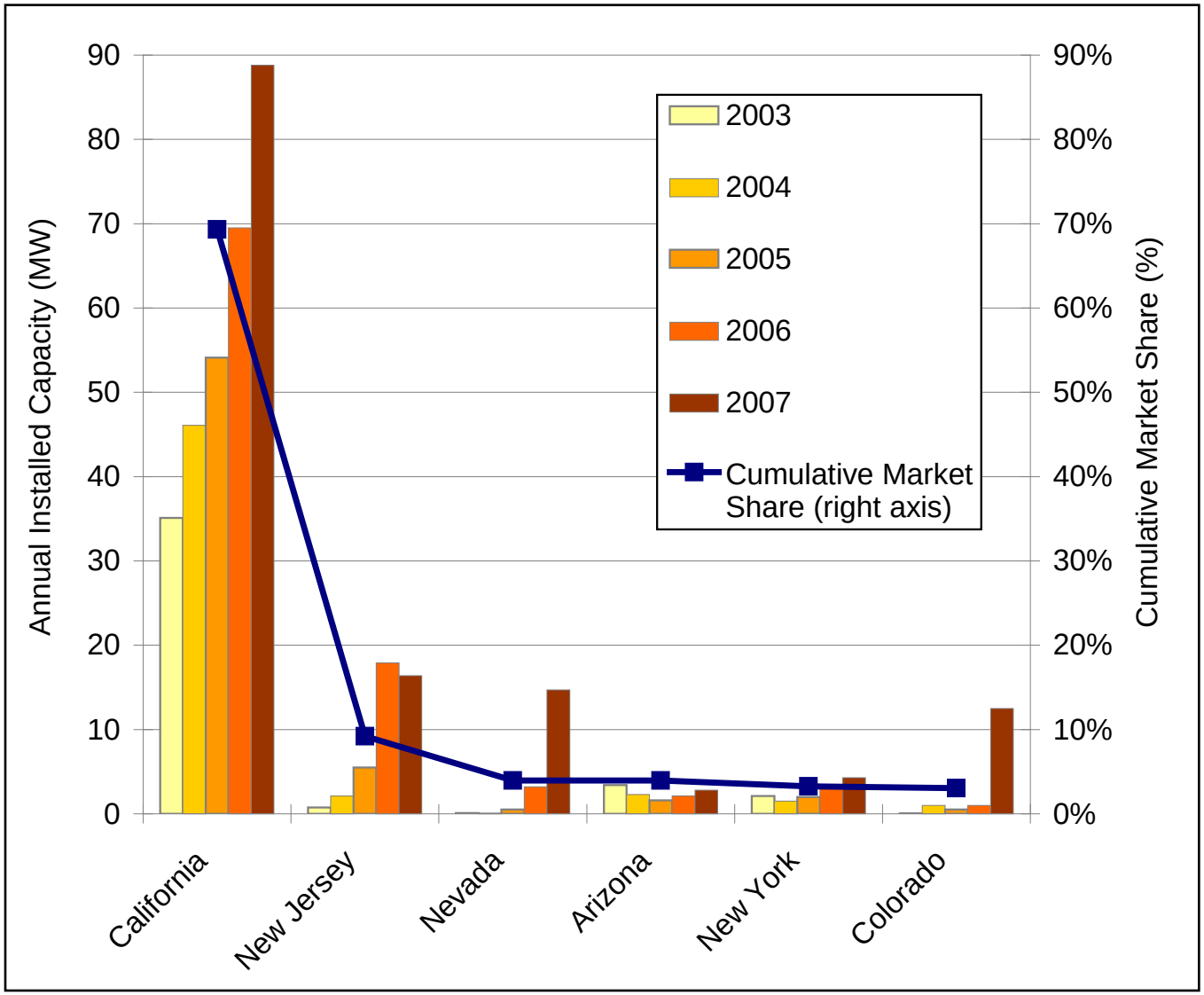
PV growing rapidly in key countries…



- Grid-connected PV is fastest growing market.
- Incentives have driven steep growth in installations.
- Average annual global growth rate has been 40+% for the past 5 years.
- Solar could capture > 30% of market share for new capacity additions during next 5-10 years.

Source: International Energy Agency (2008).

…and in a number of key states in the U.S.



Source: Larry Sherwood/IREC (2008).

- Top 6 states accounted for 92% of MW in 2007.
- Beginning to see installation of larger PV systems in 2007:
  - 14 MW at Nellis AFB, NV.
  - 8.4 MW at Alamosa, CO.
- Additional states to watch?
  - Florida,
  - Maryland,
  - Penn.,
  - Texas

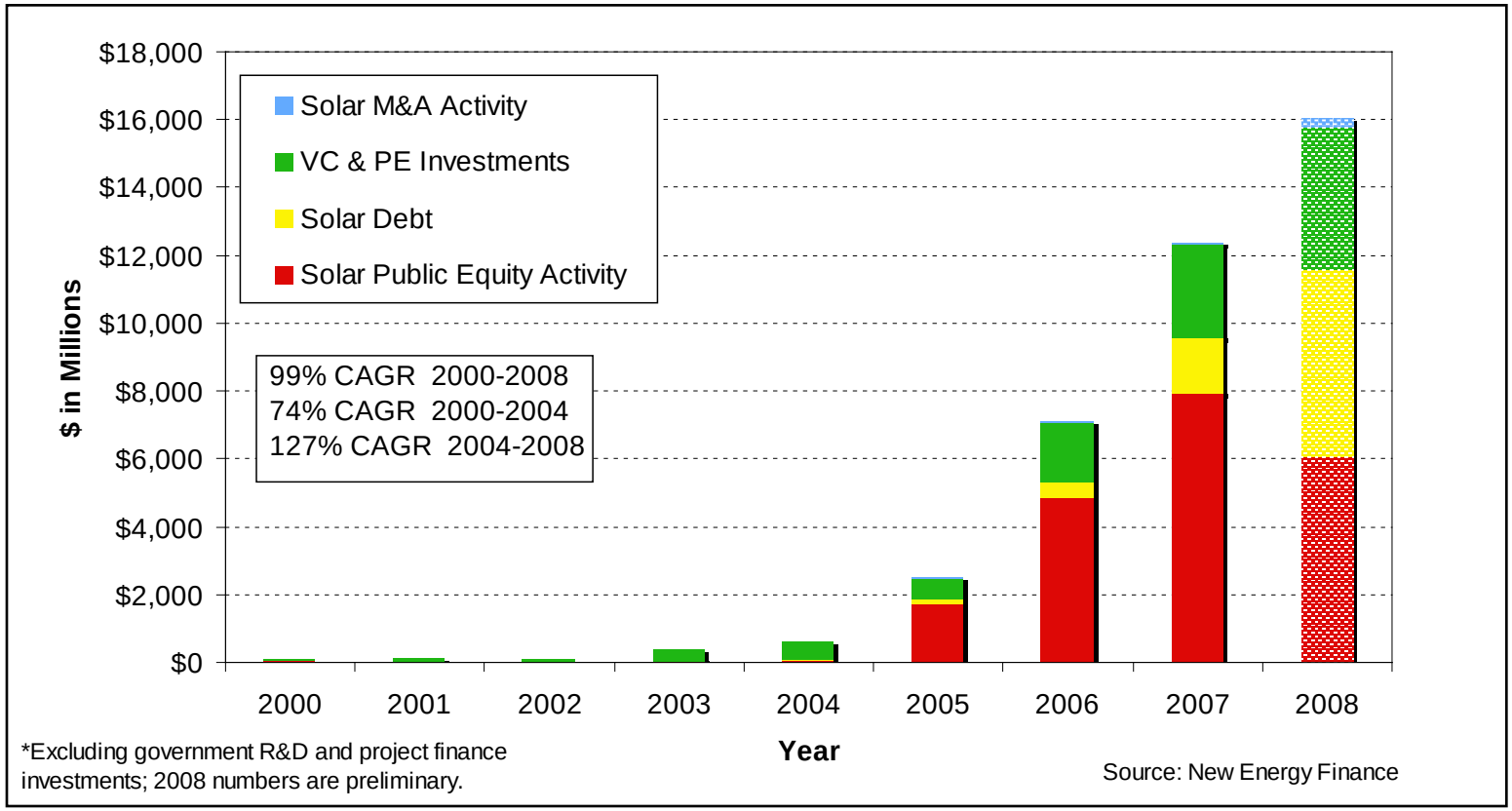
Have also seen a resurgence of interest and investment in CSP

CSP Installed Capacity

Plant name	Location	Technology Type	Year Installed	Capacity (MW)
Solar Electricity Generating Stations (SEGS)	California	Trough	1984-1991	354 total, comprised of nine, 14-80 MW plants
Saguaro	Arizona	Trough	2005	1
Nevada Solar One	Nevada	Trough	2007	64
PS10	Spain	Tower	2007	11
GEF Morocco ISCC Plant II	Morocco	Trough		6

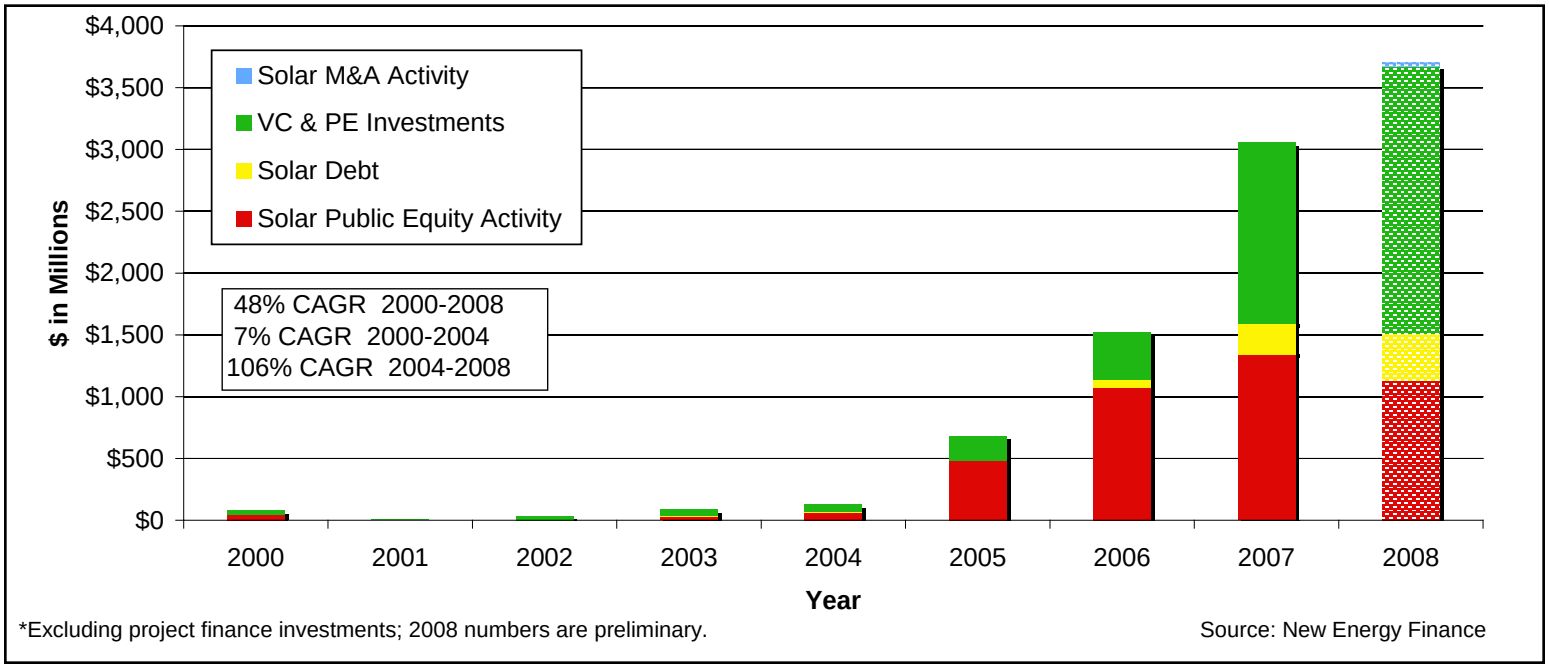
- Globally about **600 MW** of CSP is currently under construction (in Spain, North Africa, Mexico and China).
- An additional **9 GW** of CSP are in the pipeline, either announced or proposed through 2015 (43 % in US).

Total global investment in solar energy



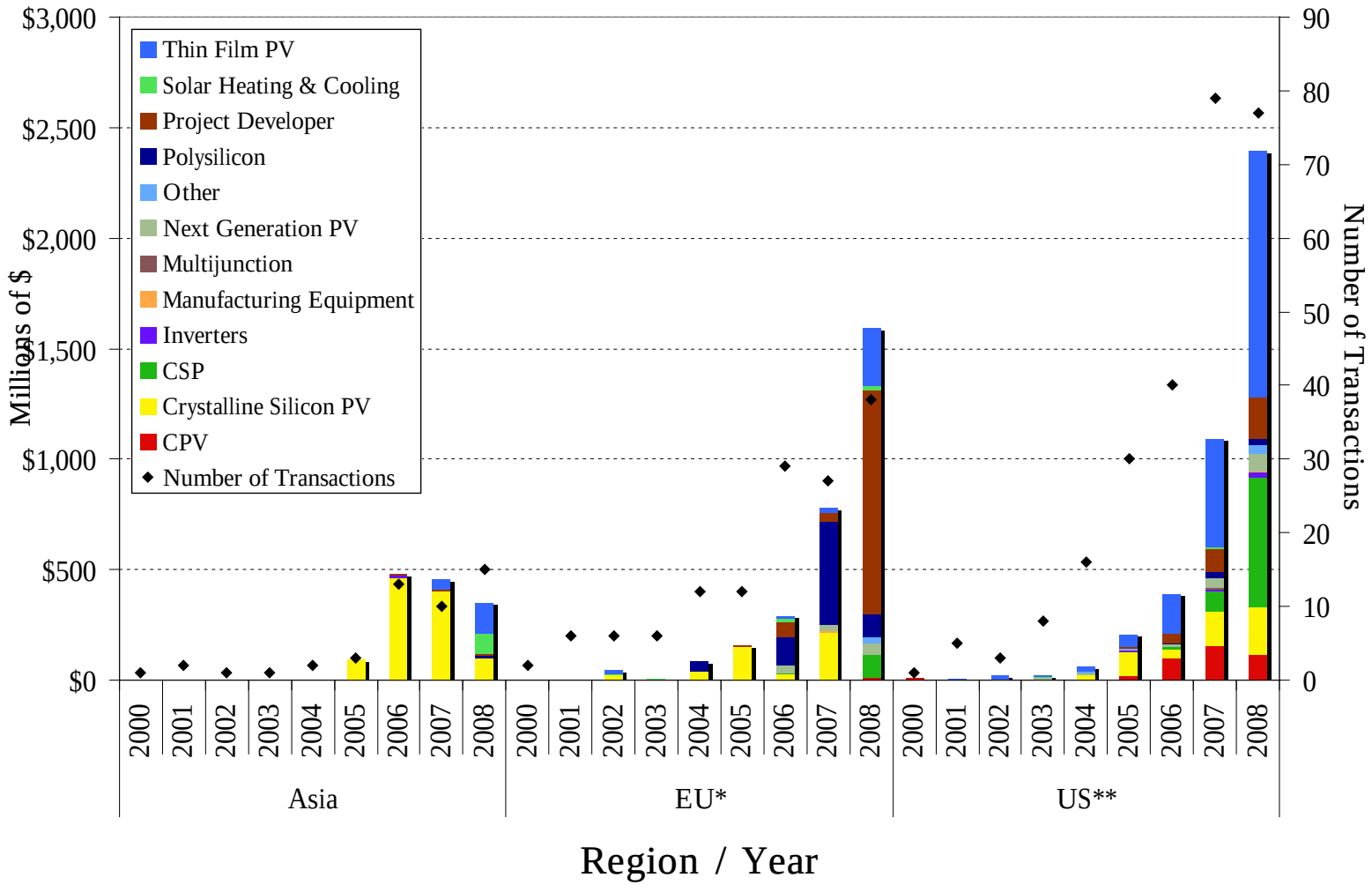
- Total global investment in solar increased from $66M in 2000 to over $16 billion in 2008.
- Venture Capital/Private Equity and Debt investments took on larger role in 2008.
- Most of 2008 investment (83%) took place during 1st three quarters of 2008 (Q4 accounted for only 17% of 2008 investment).

Total U.S. investment in solar energy

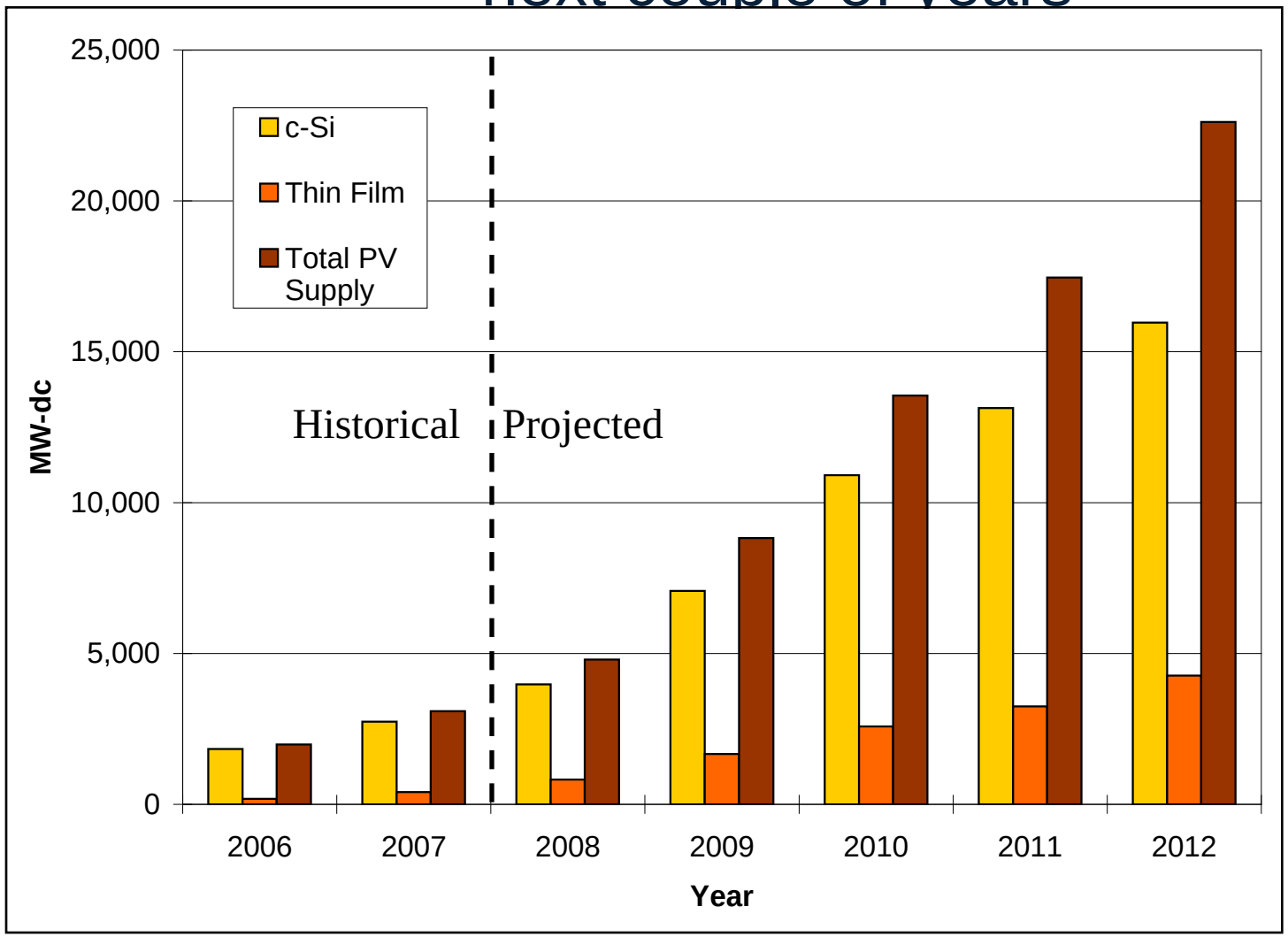


- Total U.S. investment in solar reached almost $4 billion in 2008 (~25% of global investment).
- In U.S. most of 2008 investment (87%) took place during 1st three quarters of 2008 (Q4 accounted for only 13% of 2008 investment).
- U.S. investors have been pursuing a more diverse set of technologies than investors in other regions (including thin-film PV, next generation PV, concentrating PV, and CSP).

Regional investment in solar technology



PV production is projected to grow ~ 5x over the next couple of years



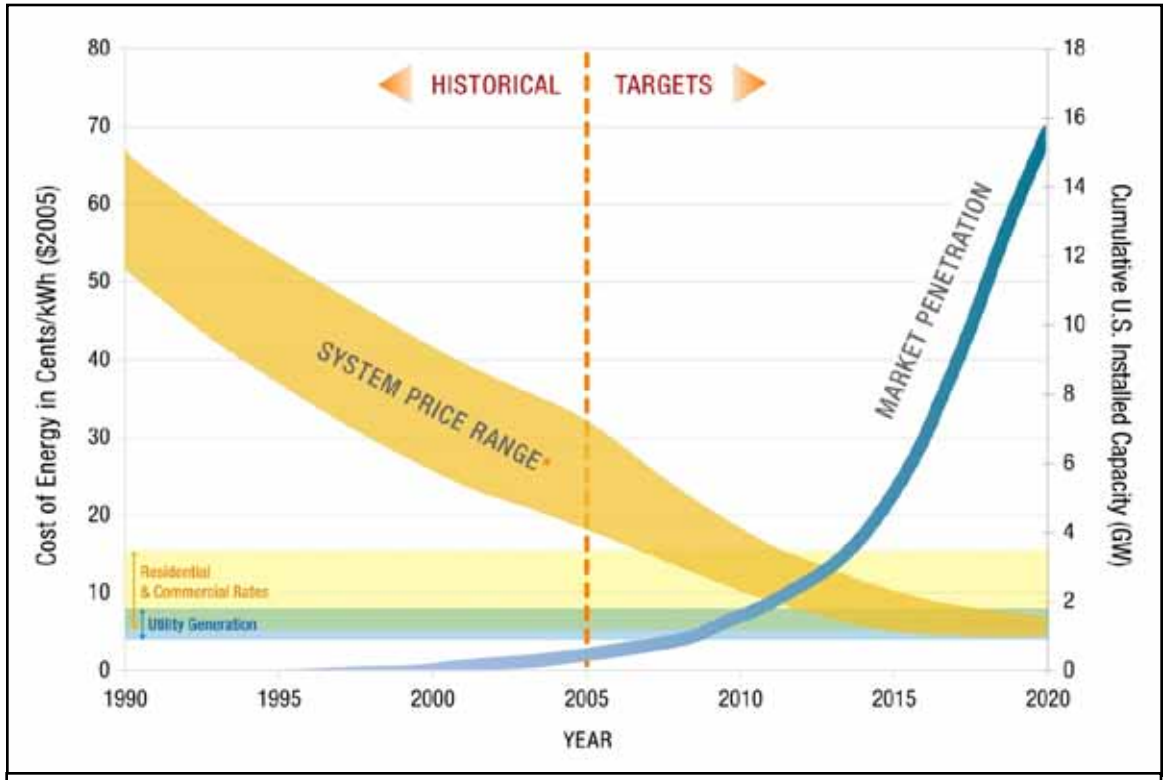
- c-Si is expected to remain dominant.
- But, thin-film is expected to grow more rapidly.
- Financial crisis has led some analysts to lower their projections (10-25%).

Source: Median values from projections by 11 industry analysts (Nov 2007 – Jan 2009).

PV is expected to reach grid parity in U.S. between 2010 and 2015

But many challenges:

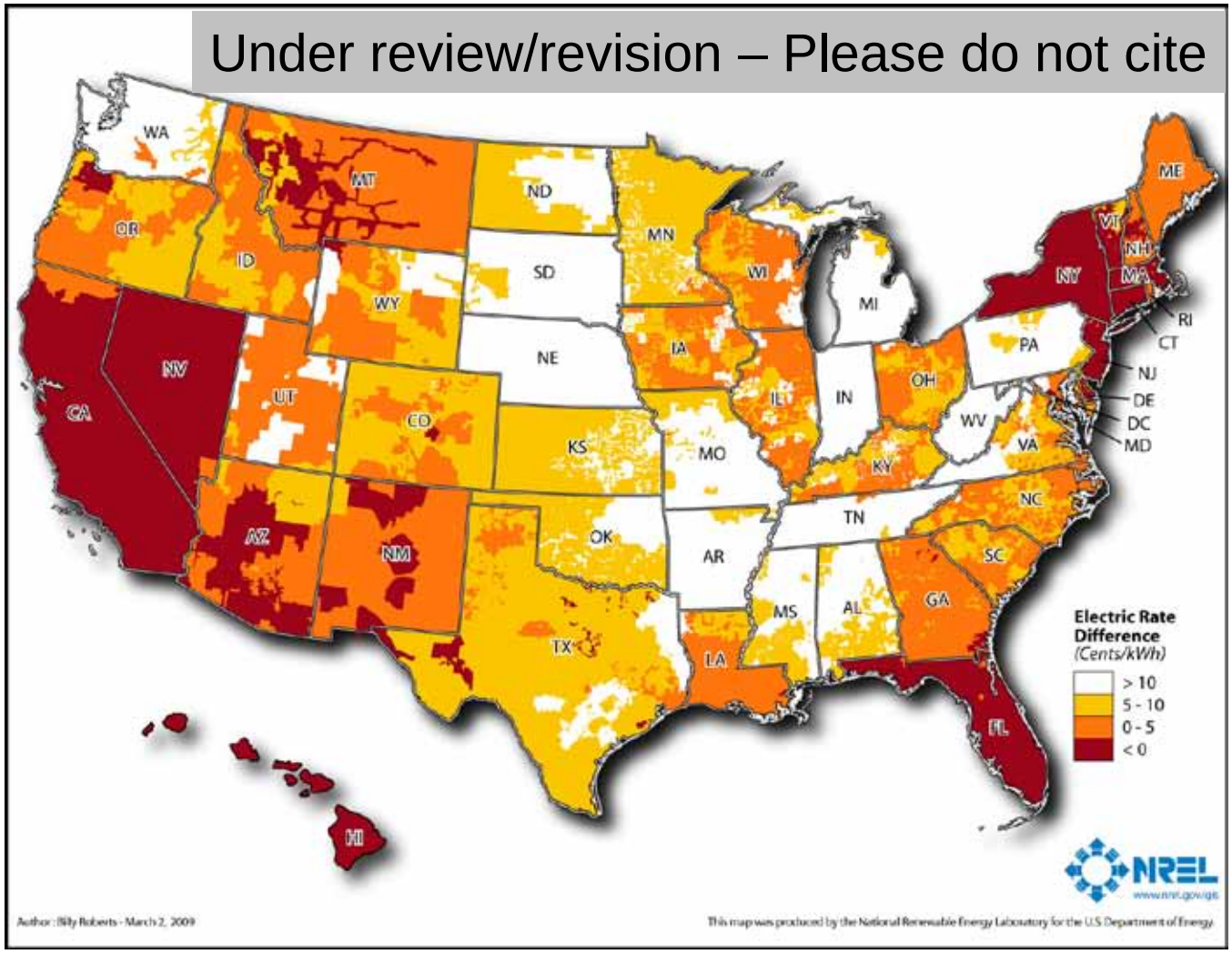
- Reducing cost
- Improving performance and reliability
- Maintaining balance between supply and demand (polysilicon supply, manufacturing capacity, distribution/ installation networks)
- Understanding and acceptance by financial sector, regulators, utilities
- Integrating solar with other systems (grid, buildings)



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

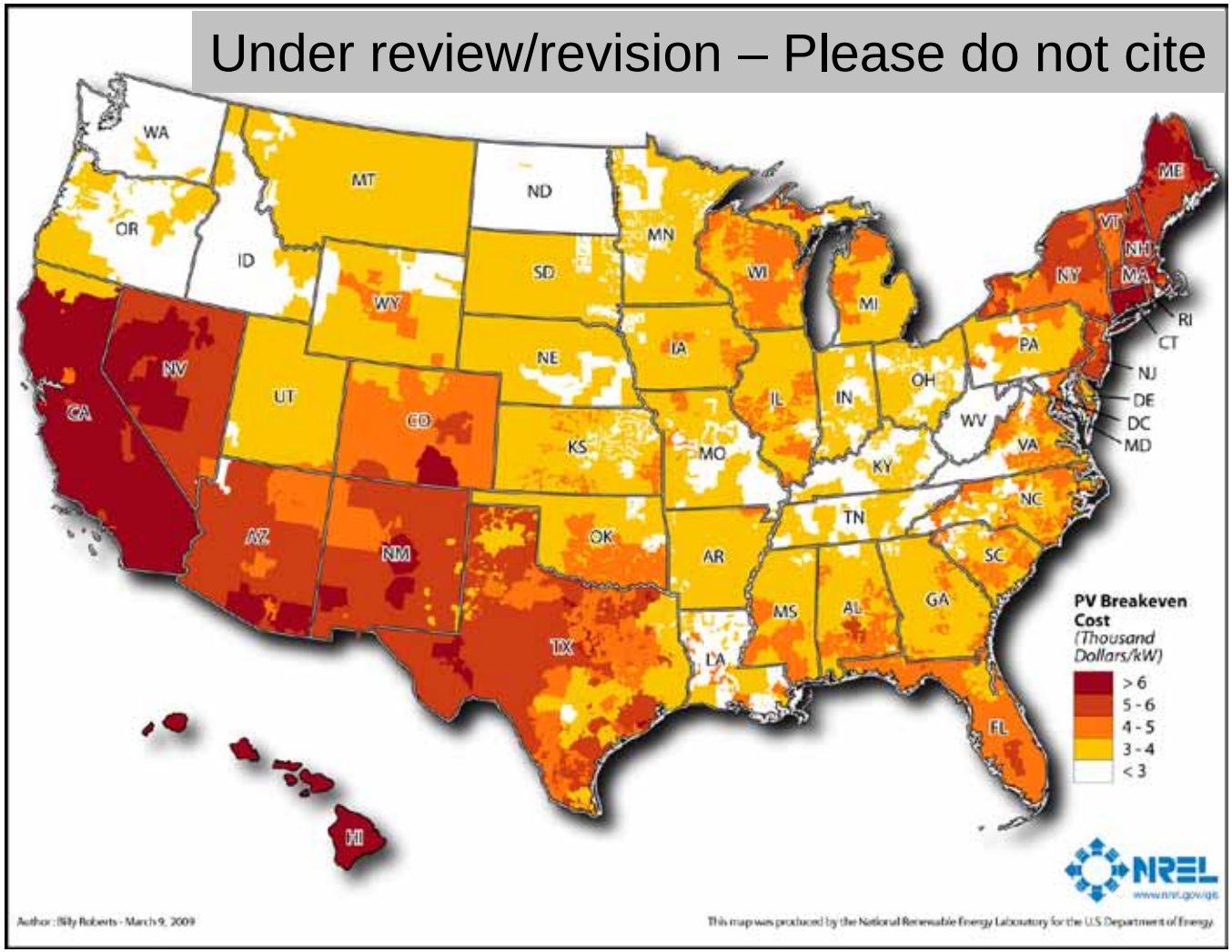
2009 residential PV and electricity price differences with existing incentives

- Analysis for 1000 largest utilities in the U.S.
- Key drivers for PV are incentives, electricity prices and quality of the solar resource.



2015 residential breakeven cost with federal ITC but no state incentives

- At $5/W, attractive in 98 of 1,000 largest utilities, which provide ~25% of U.S. residential electricity sales.
- At $4/W attractive in 328 utilities, ~42% of sales.
- At $3/W attractive in 743 utilities, ~80% of sales.



A number of factors are driving strong growth in the solar industry

- Federal, state, and local policy incentives.
- Market volatility, especially with respect to natural gas and oil.
- Climate change and likely carbon regulations.
- Energy security issues.
- Need for increased energy production to meet growing demand (China, India, etc.).
- Interest from financial community in “next big thing”.

Coal Mining is VERY Dangerous

USA TODAY

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Coal mine deaths spike upward

Posted 1/1/2007 10:28 PM ET

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Enlarge AP

Twelve black ribbons are tied on the perimeter fence of the Sago Mine in Tallmansville, W . Va., Jan. 8, 2006, in memory of the 12 coal miners who died here after a mine explosion.

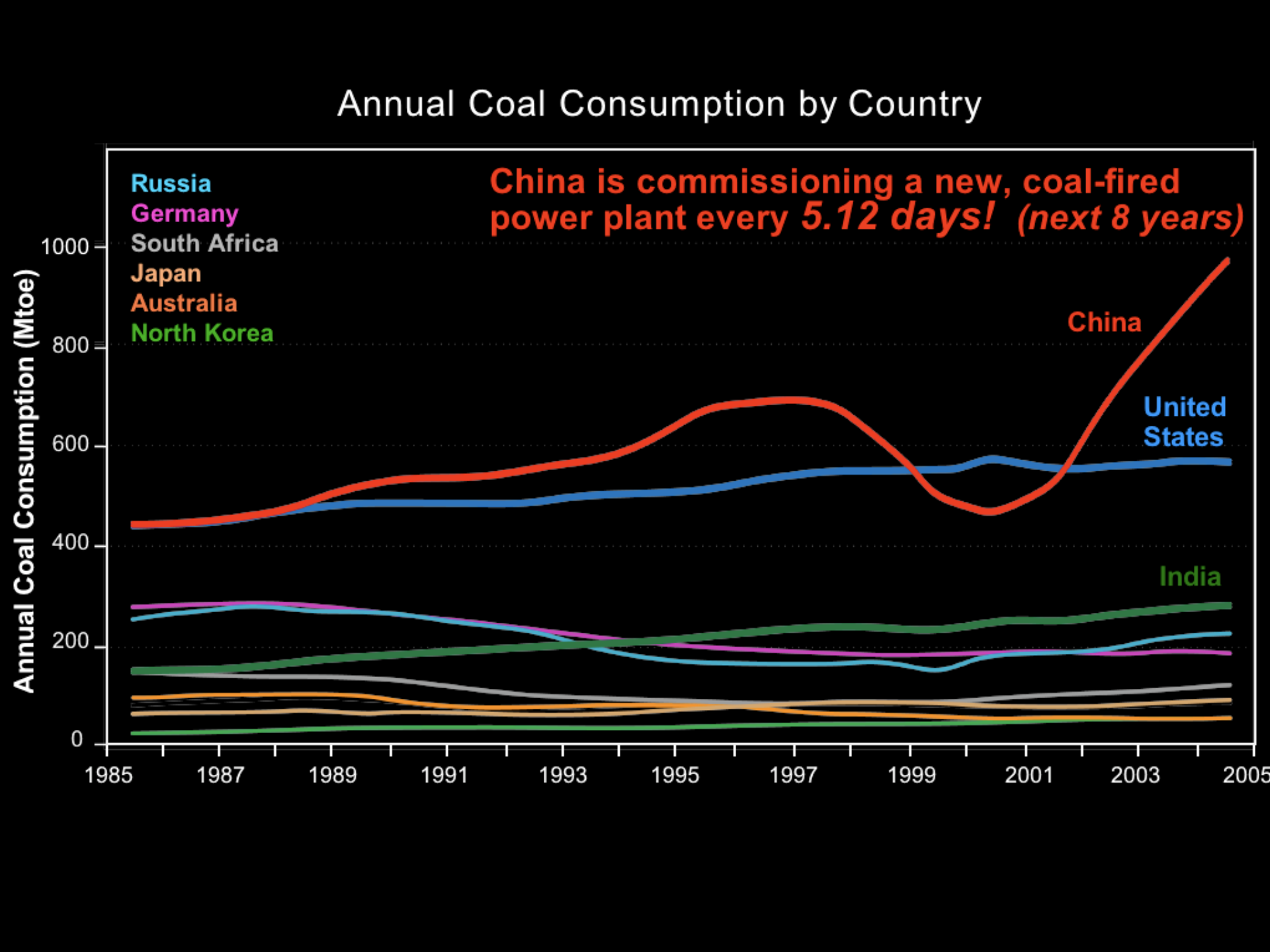
By Thomas Frank, USA TODAY

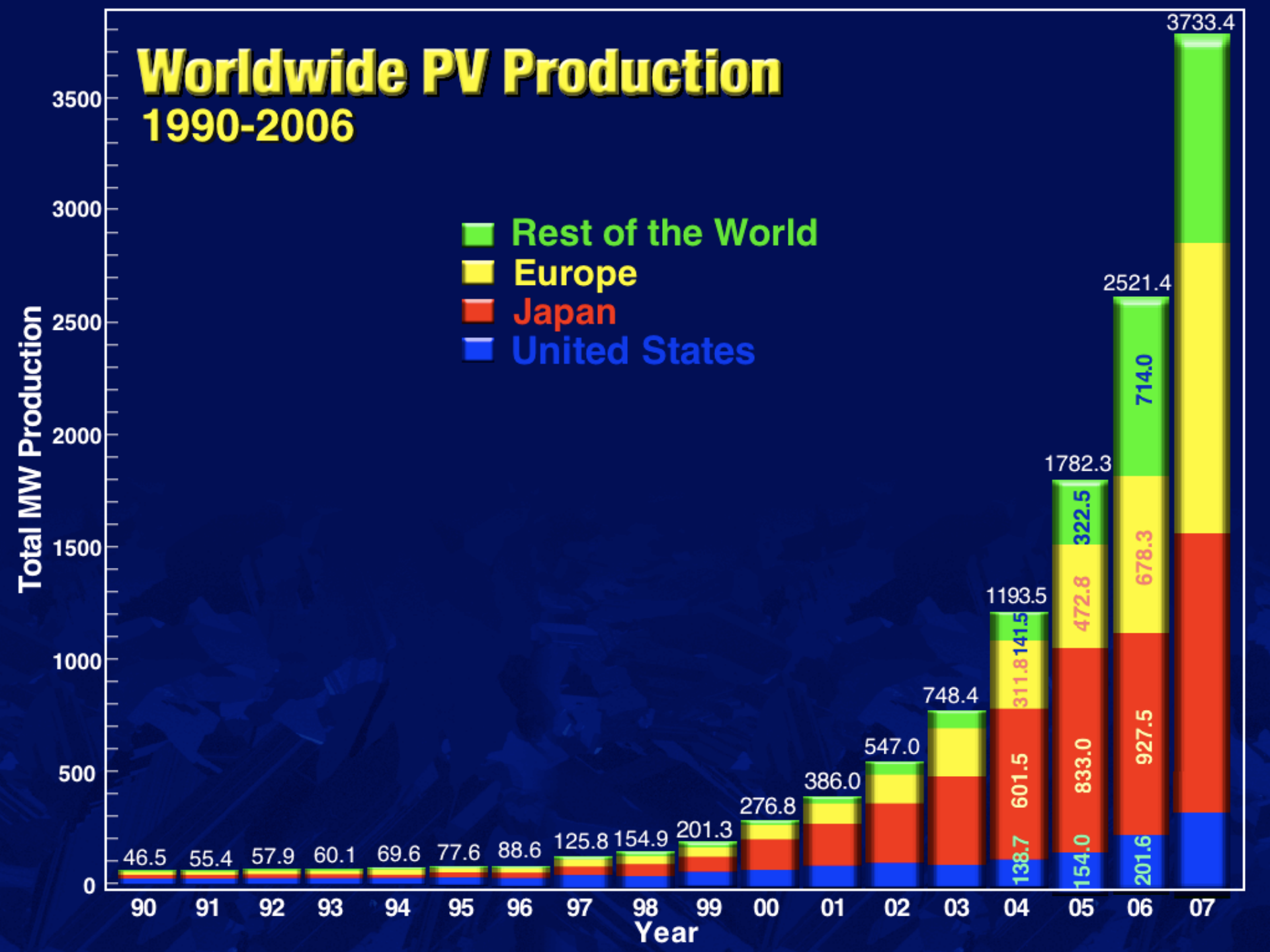
- U.S. has >700 mining disasters with five or more fatalities.
- U.S. pre-1930 had > 2,000 coal mining fatalities annually.
- China, 1950-today: between 4,000 and 6,000 miners die every year in coal-mine accidents
- Coal mining is the **ONLY** "industrial process" to directly claim more than 100,000 lives

Typical Coal Plant Generates

- 3,700,000 tons of carbon dioxide (CO_2),
  the primary human cause of global warming--as much carbon dioxide as cutting down 161 million trees.
- 10,000 tons of sulfur dioxide (SO_2),
  which causes acid rain that damages forests, lakes, and buildings, and forms small airborne particles that can penetrate deep into lungs.
- 500 tons of small airborne particles,
  which can cause chronic bronchitis, aggravated asthma, and premature death, as well as haze obstructing visibility.
- 10,200 tons of nitrogen oxide (NO_x),
  as much as would be emitted by half a million late-model cars. NOx leads to formation of ozone (smog) which inflames the lungs, burning through lung tissue making people more susceptible to respiratory illness.
- 720 tons of carbon monoxide (CO),
  which causes headaches and place additional stress on people with heart disease.
- 220 tons of hydrocarbons,
  volatile organic compounds (VOC), which form ozone.
- 170 pounds of mercury,
  where just 1/70th of a teaspoon deposited on a 25-acre lake can make the fish unsafe to eat.
- 225 pounds of arsenic,
  which will cause cancer in one out of 100 people who drink water containing 50 parts per billion.
- 114 pounds of lead, 4 pounds of cadmium, other toxic heavy metals, and trace amounts of uranium…

Source: Union of Concerned Scientists


Annual Coal Consumption by Country
China is commissioning a new, coal-fired power plant every 5.12 days! (next 8 years)
Russia
Germany
South Africa
Japan
Australia
North Korea
China
United States
India
Annual Coal Consumption (Mtoe)
0
200
400
600
800
1000
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005


Worldwide PV Production
1990-2006
Rest of the World
Europe
Japan
United States
Total MW Production
0
500
1000
1500
2000
2500
3000
3500
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
154.9
201.3
276.8
386.0
547.0
748.4
1193.5
1782.3
2521.4
3733.4
138.7
601.5
311.8
141.5
154.0
833.0
472.8
322.5
201.6
927.5
678.3
714.0
90
91
92
93
94
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98
99
00
01
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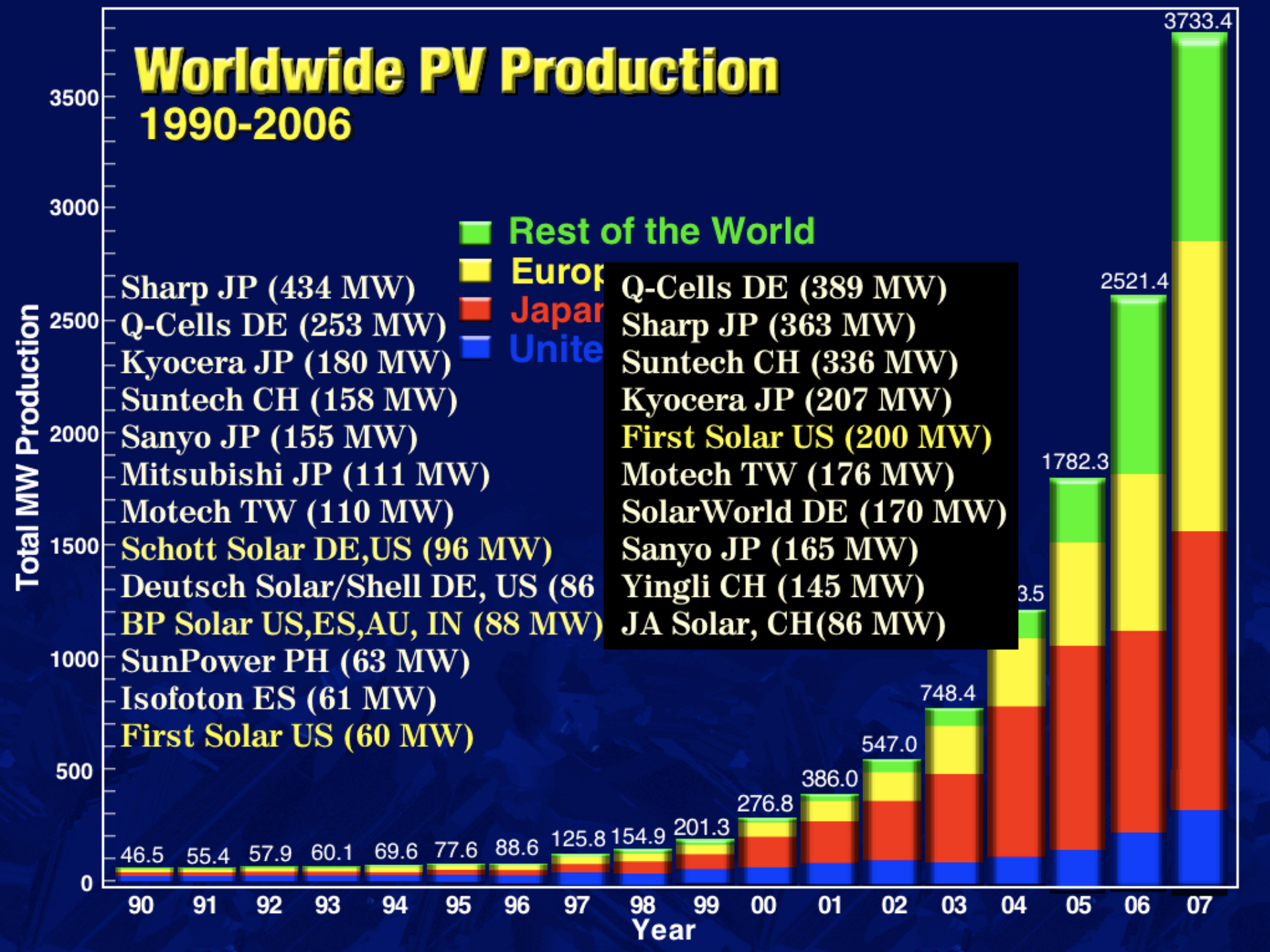
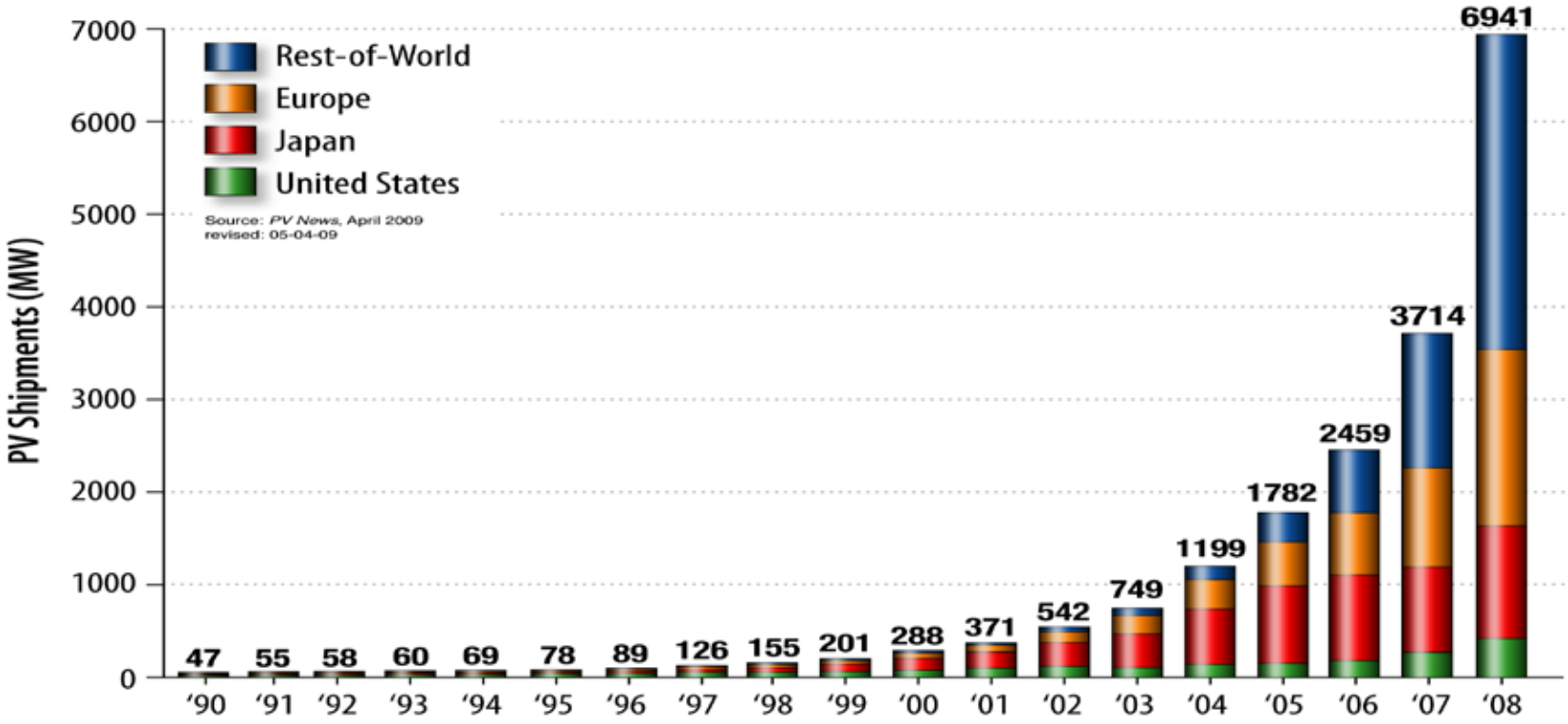
04
05
06
07
Year


Worldwide PV Production
1990-2006
Rest of the World
Europ
Japar
Unite
Sharp JP (434 MW)
Q-Cells DE (253 MW)
Kyocera JP (180 MW)
Suntech CH (158 MW)
Sanyo JP (155 MW)
Mitsubishi JP (111 MW)
Motech TW (110 MW)
Schott Solar DE,US (96 MW)
Deutsch Solar/Shell DE, US (86
BP Solar US,ES,AU, IN (88 MW)
SunPower PH (63 MW)
Isofoton ES (61 MW)
First Solar US (60 MW)
Q-Cells DE (389 MW)
Sharp JP (363 MW)
Suntech CH (336 MW)
Kyocera JP (207 MW)
First Solar US (200 MW)
Motech TW (176 MW)
SolarWorld DE (170 MW)
Sanyo JP (165 MW)
Yingli CH (145 MW)
JA Solar, CH(86 MW)
Total MW Production
0
500
1000
1500
2000
2500
3000
3500
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
154.9
201.3
276.8
386.0
547.0
748.4
1782.3
2521.4
3733.4
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04
05
06
07
Year

PV Economics

An economist is an expert who will know tomorrow why the things he predicted yesterday didn't happen today.
-- Laurence J. Peter --



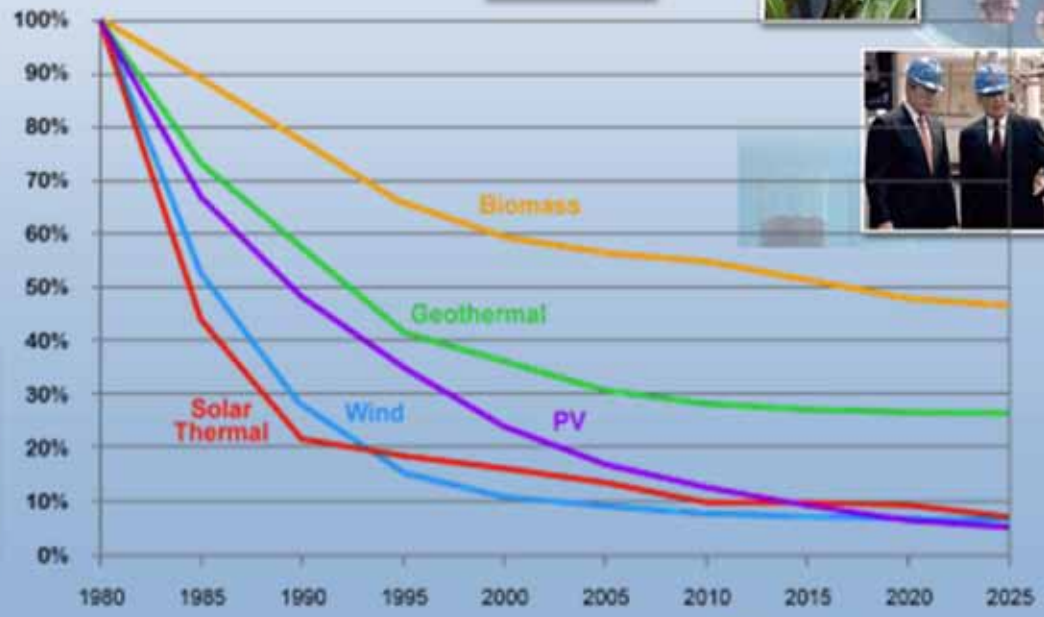
Levelized Cost of Electricity

Figure 3. Levelized Cost of Electricity (LCOE) Across Various Energy Sources

	% of global electricity	Cost ($/kWh)
Traditional Power		
Gas	15%	$0.04 - $0.05
Coal	40%	$0.05 - $0.06
Nuclear	25%	$0.10 - $0.15
Renewable Energy		
Wind	~1-2%	$0.04 - $0.06
Geothermal	<1%	$0.05 - $0.07
Hydro	20%	$0.05 - $0.11
Solar	**~1%**	**$0.15 - $0.45**

Source: Citi Investment Research

Past Investments Have Yielded Impressive Cost Reductions



NREL National Renewable Energy Laboratory

Cost of Solar Electricity

Cost of PV Generated Energy

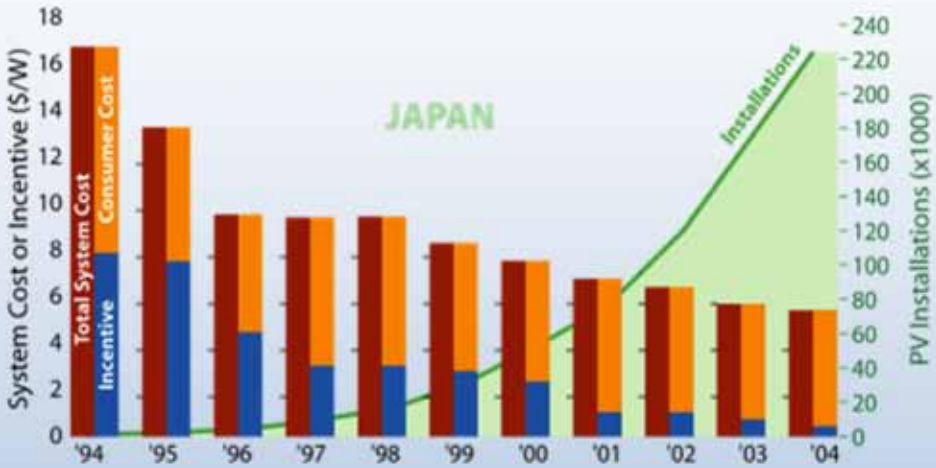
- Before incentives, 15 to 35 cents per kWh depending on location, size and amount of storage (independence)

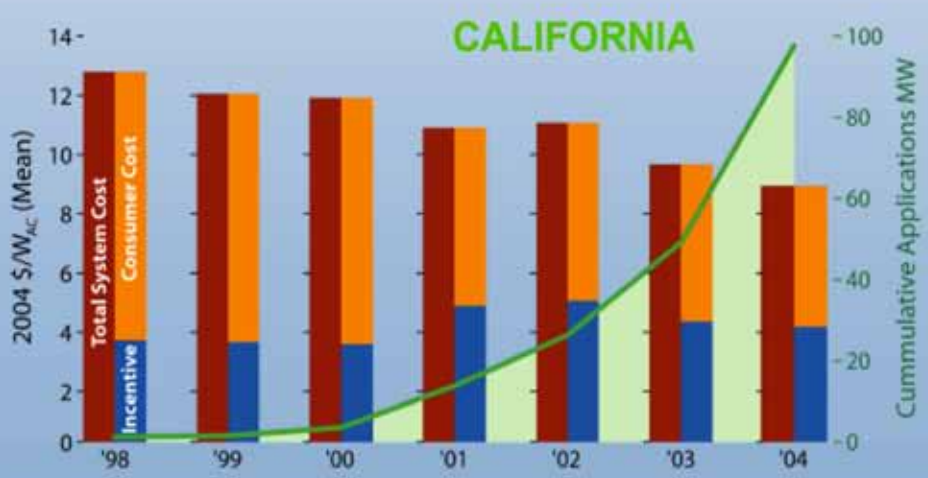
Cost of PV Installed Power Capacity

- Typical grid-tied residence systems range from $6-10/watt, before incentives
- Grid independent systems (depending upon location, amount of storage, backup generator, etc.) are $20/watt, or more

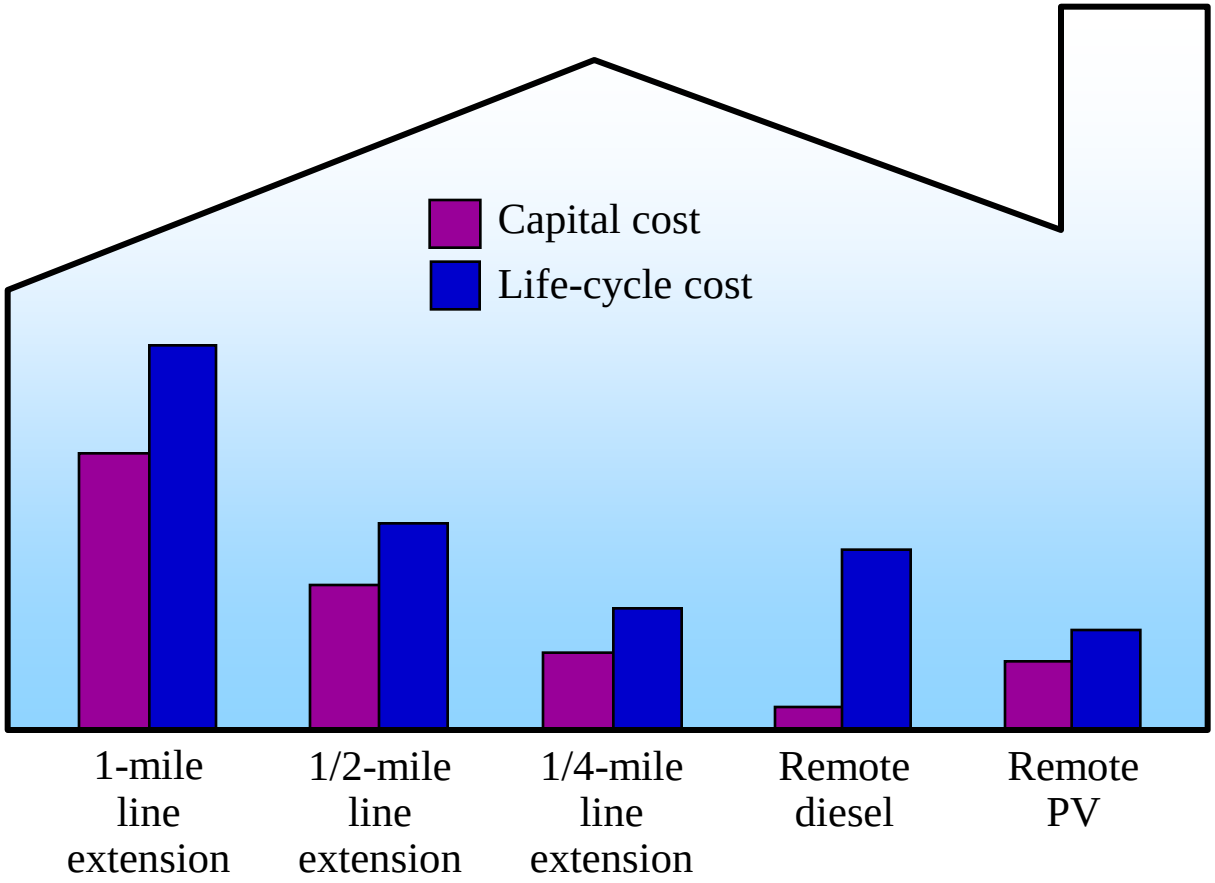
Ref: Byron Stafford, NREL

Worldwide Markets Have Driven Cost Reductions – Solar PV Example





Total Costs for Remote Power



Installed cost of PV often competes with line extensions and remote diesels.

Ref: Byron Stafford, NREL

What's Drives the Current Market?

International:

- Demand exceeds supply
- $3–4 billion per year industry
- 35% average annual sales growth
- Manufacturing costs dropping
- Sales price steady (or rising slightly)

Domestic:

- Relatively high capital cost
- Cannot compete with established central power
- Cost-effective utility markets limited
- PV often competes on capital cost basis
- PV rarely competes on energy cost basis

Ref: Byron Stafford, NREL

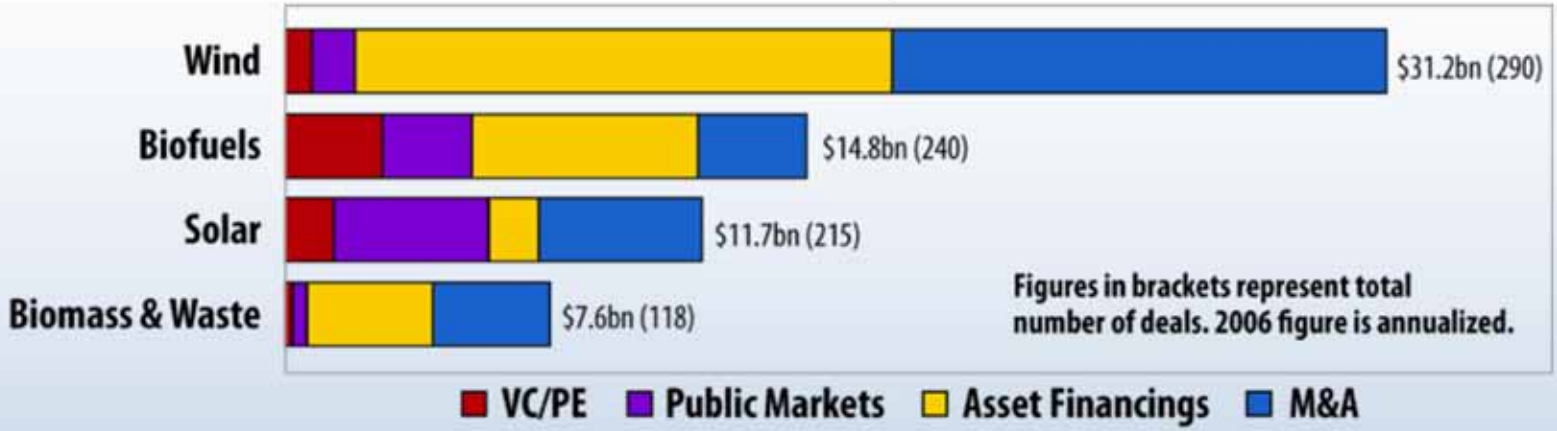
What Will Drive Future PV Markets?

- Increasing international and domestic demand
- Global uncertainties, e.g., weather, oil supply, etc.
- Increasing production capacity
- Lower manufacturing costs and sale prices
- Improving efficiencies, lifetimes, system reliability
- Convenient interconnection agreements/processes
- Well-defined and accepted interconnection standards
- Federal and state support, e.g., tax incentives, buy-downs, etc.
- Regulatory measures (reducing paperwork at ~$1/W)
- Grid extensions, smart grid, electricity storage

Ref: Byron Stafford, NREL

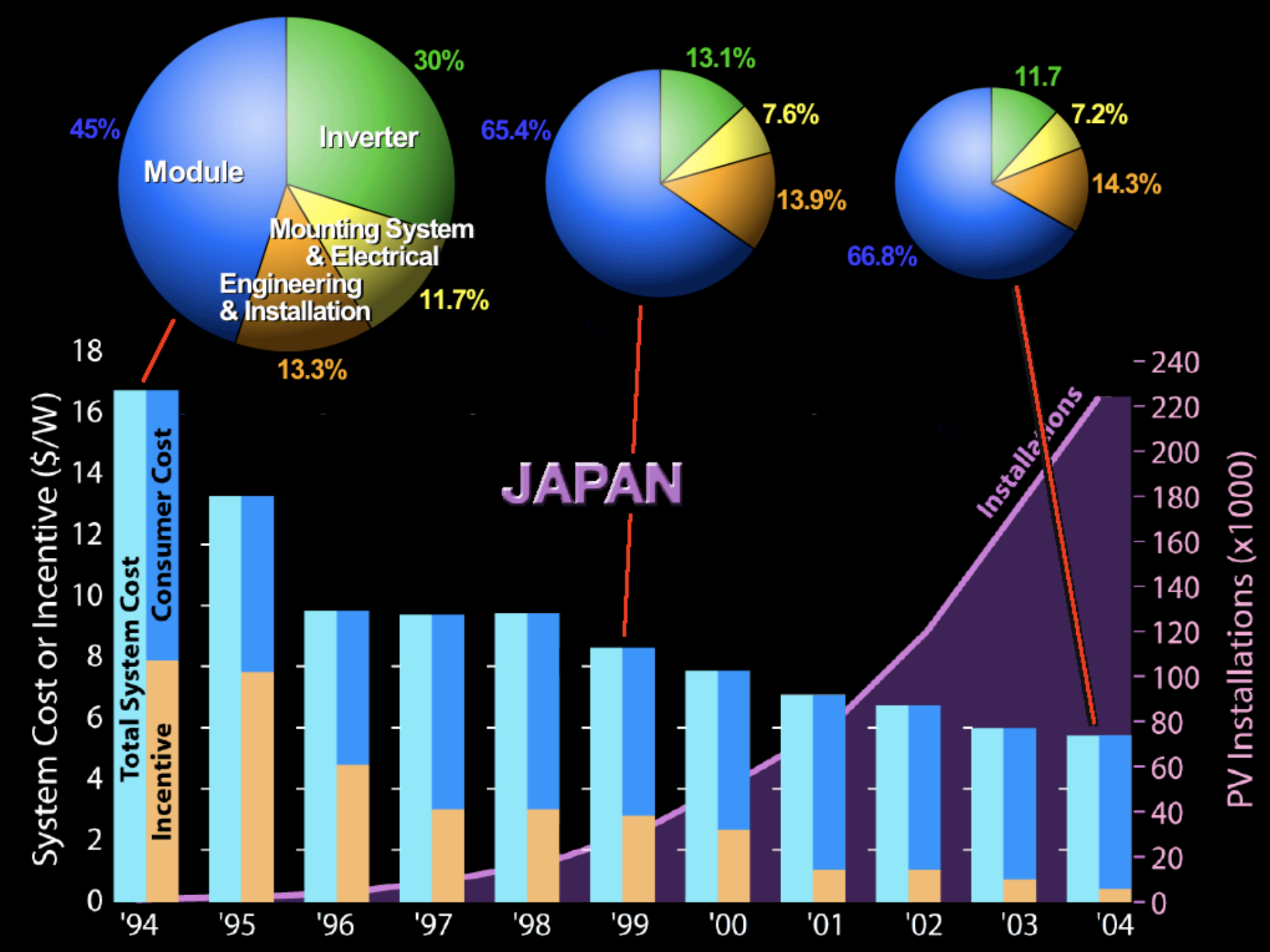
Money Is Flowing Into the Sector

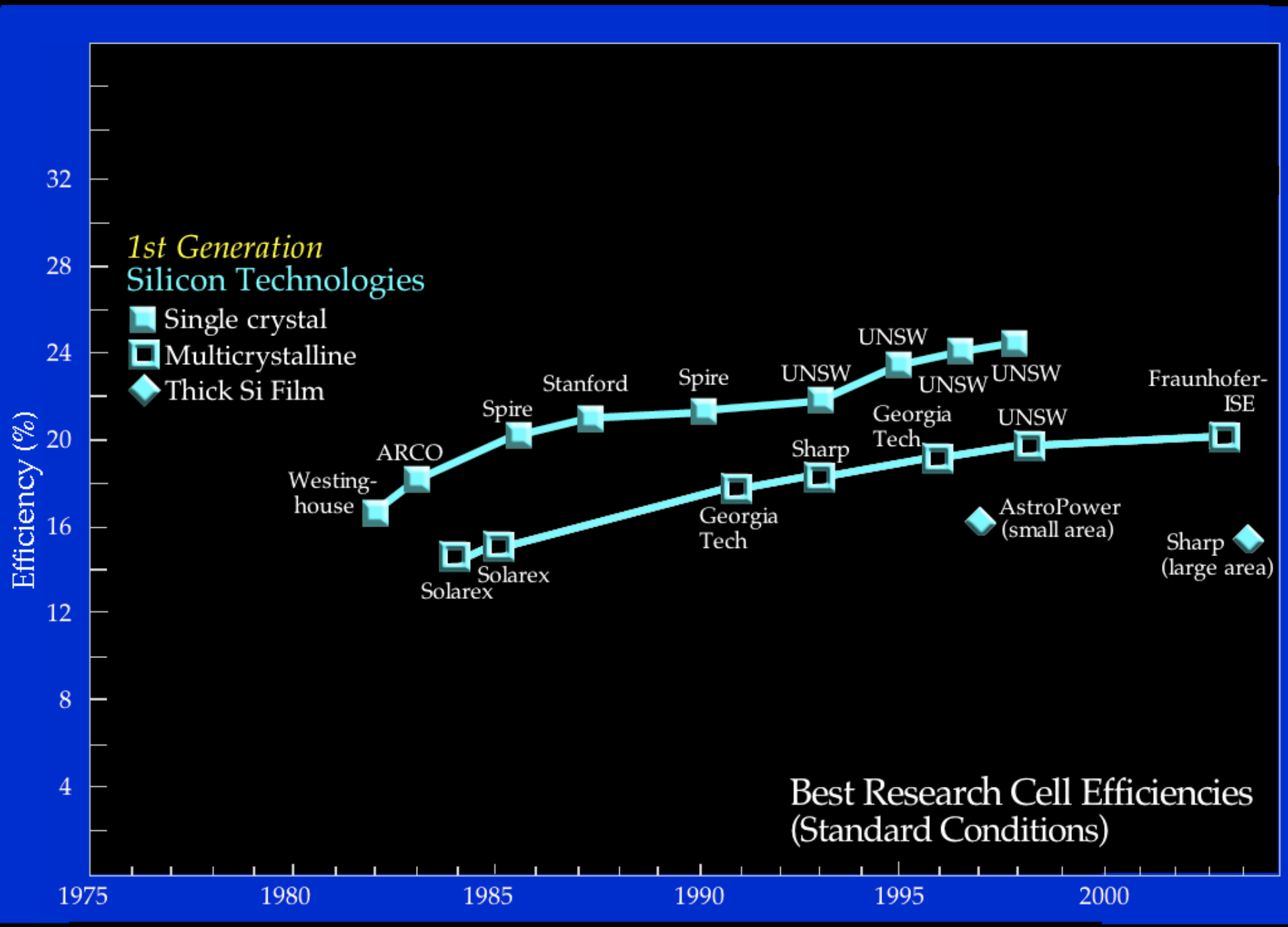
2006 Investment and M&A – By Sector and Asset Class



Annual VC Investment Volume – 2001-2004 Compared With 2005-2006

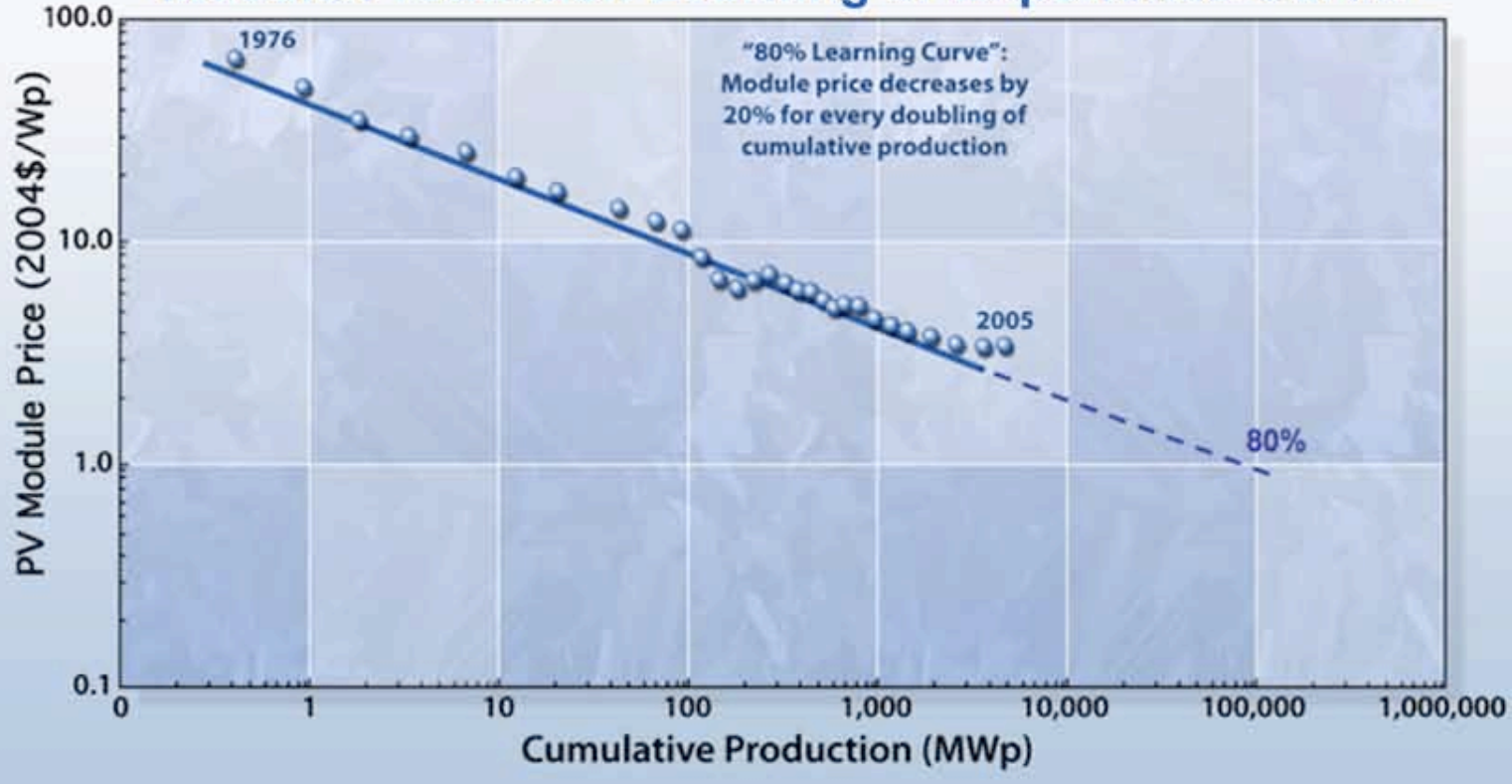
Source: New Energy Finance 2007


45%
Module
30%
Inverter
Mounting System
& Electrical
Engineering
& Installation
11.7%
13.3%
65.4%
13.1%
7.6%
13.9%
66.8%
11.7
7.2%
14.3%
JAPAN
Total System Cost
Consumer Cost
Incentive
Installations
System Cost or Incentive ($/W)
PV Installations (x1000)
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240
'94
'95
'96
'97
'98
'99
'00
'01
'02
'03
'04


1st Generation
Silicon Technologies
Single crystal
Multicrystalline
Thick Si Film
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
Westing-
house
ARCO
Spire
Stanford
Spire
UNSW
UNSW
UNSW
UNSW
Solarex
Solarex
Georgia
Tech
Sharp
Georgia
Tech
UNSW
AstroPower
(small area)
Fraunhofer-
ISE
Sharp
(large area)
Best Research Cell Efficiencies
(Standard Conditions)

Technololgy Investment Pathways

Module Production Learning or Experience Curve



Applied Science & Technology

1st Generation PV

- **Silicon**

Evolutionary

(3-5 years)

Technololgy Investment Pathways

Industry-Driven

Applied Science & Technology

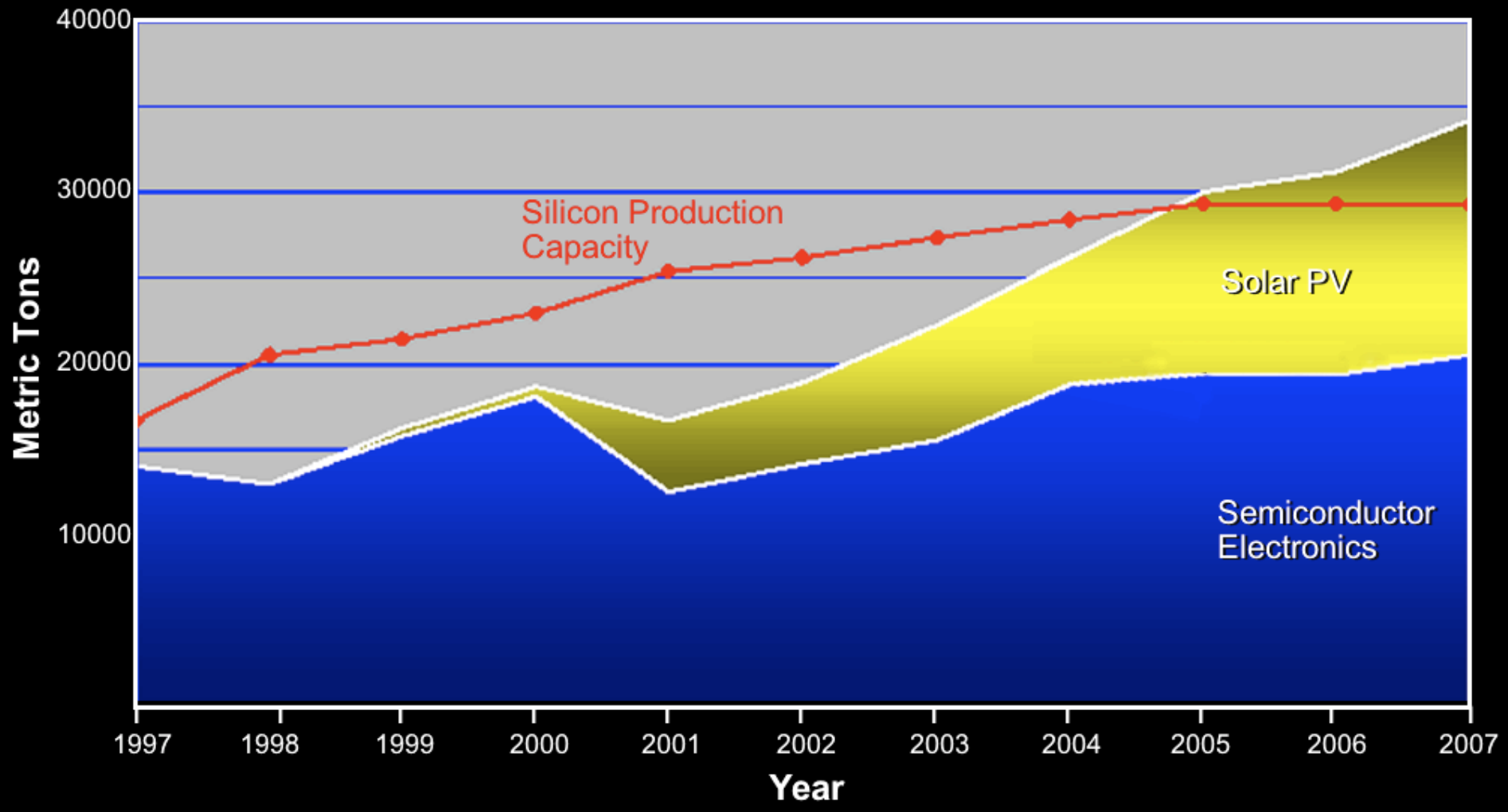
1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

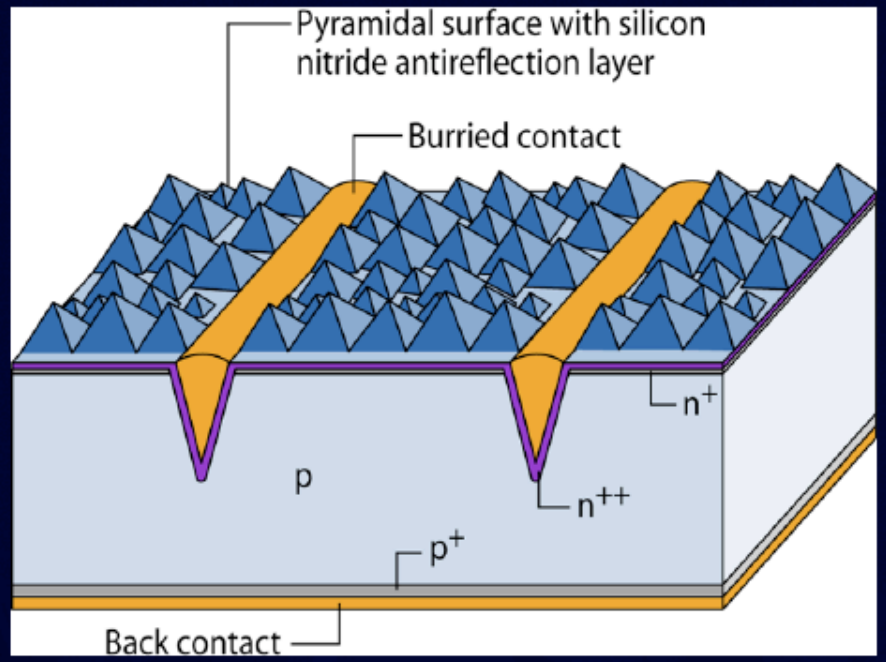
Accelerated Evolutionary

(3-5 years)

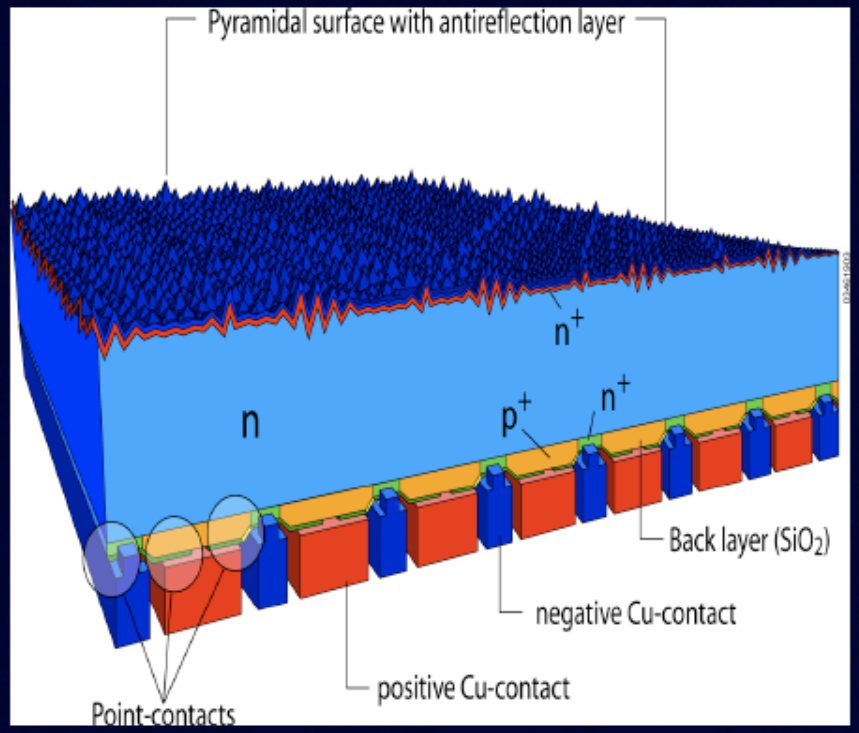
The Silicon Issue



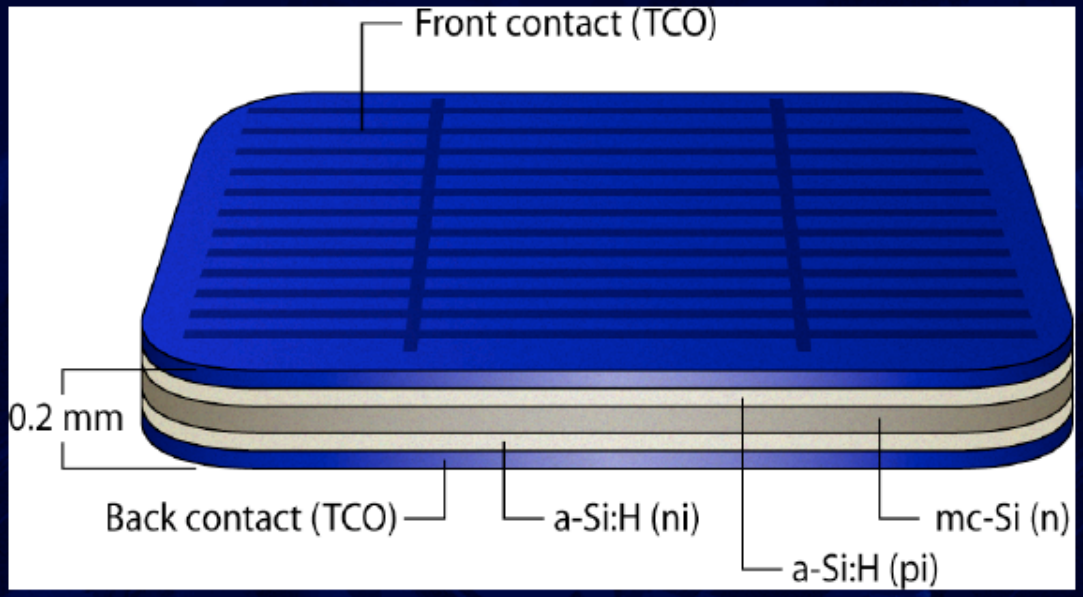
PV Si 20% Club



BP Saturn



SunPower Cell



Sanyo HIT Cell

Benefits . . .

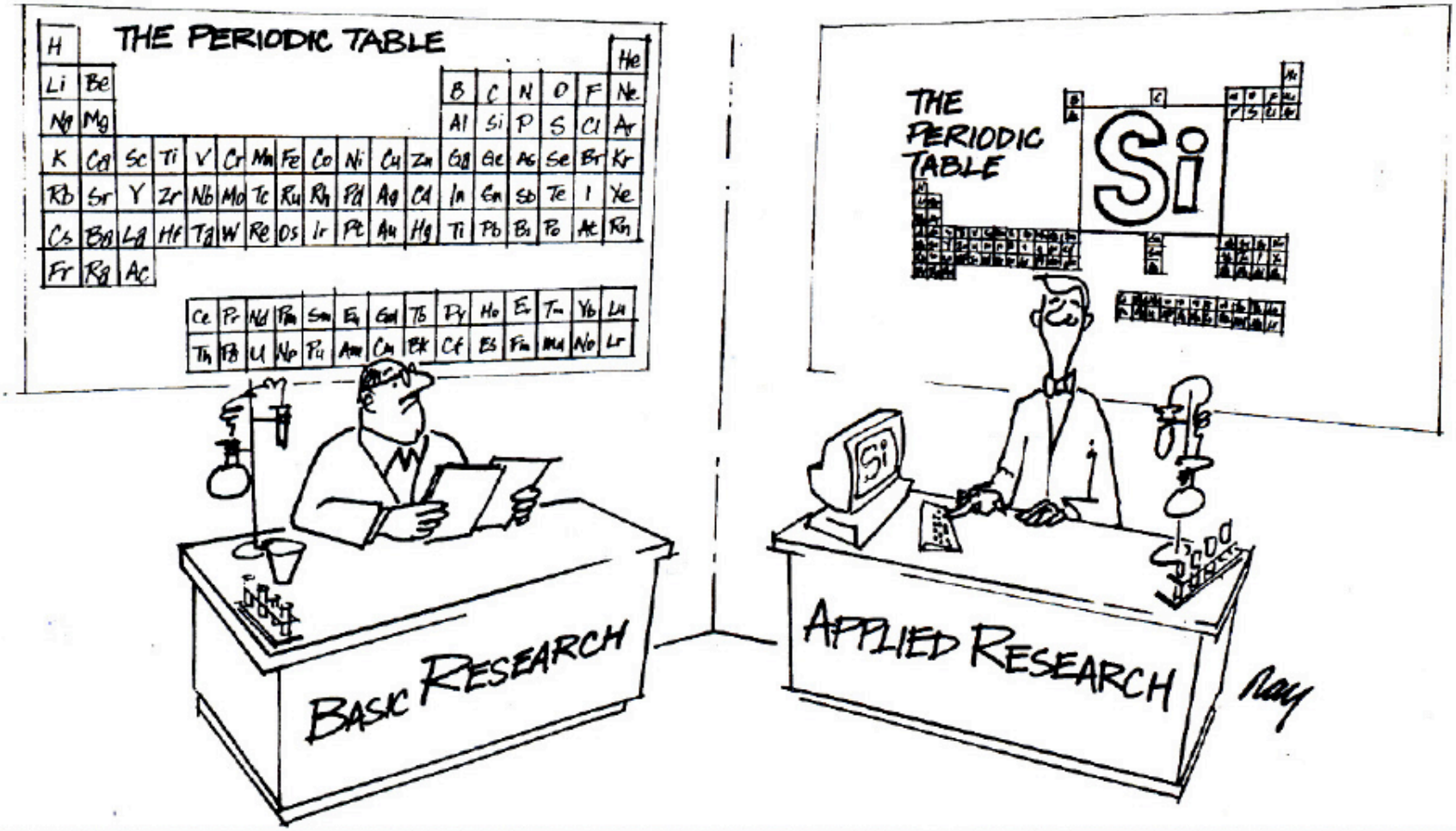
Made the Si industry examine itself.

- Better Si material utilization
- Process improvements
- Performance improvements

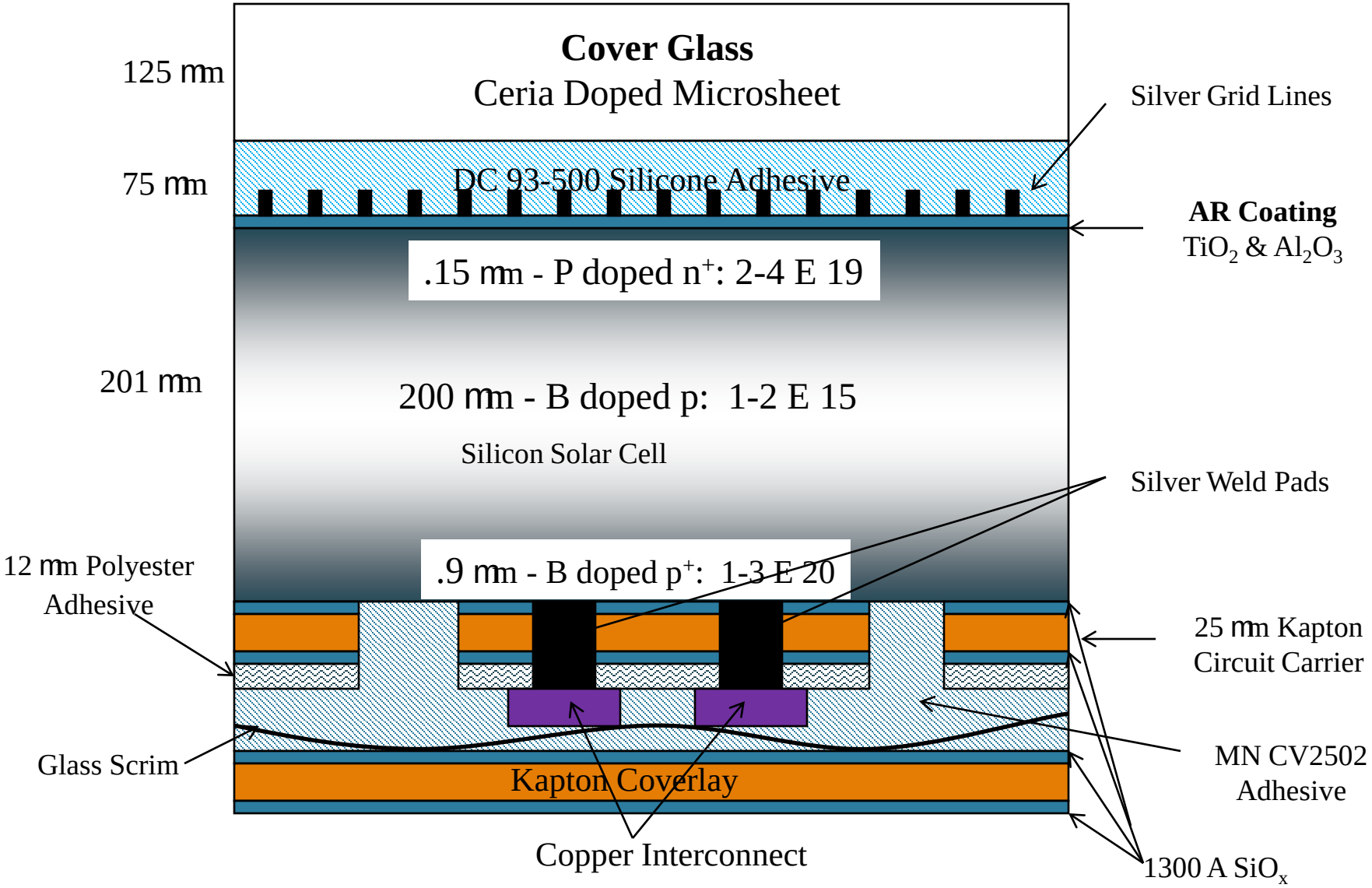
Accelerated other technologies.

- Thin films into the marketplace
- Established companies look at alternatives

Problem: Si Shortage

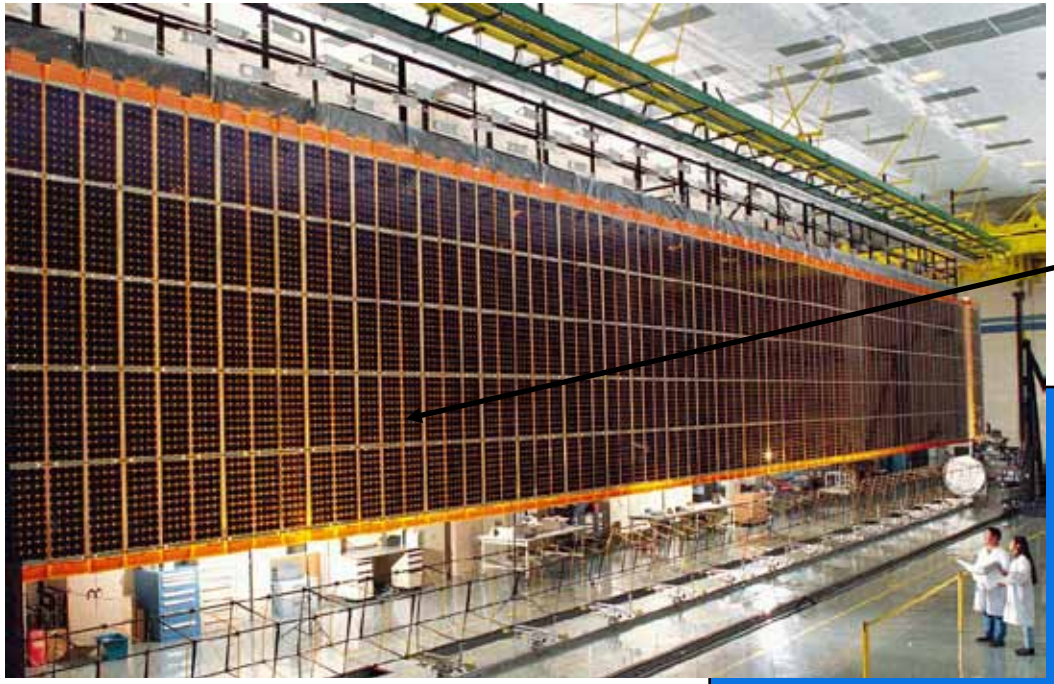

THE PERIODIC TABLE
BASIC RESEARCH
THE PERIODIC TABLE
Si
APPLIED RESEARCH

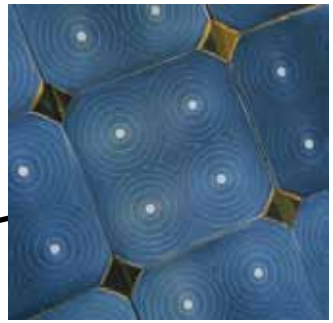
ISS Solar Array Blanket Cross Section



ISS Solar Arrays

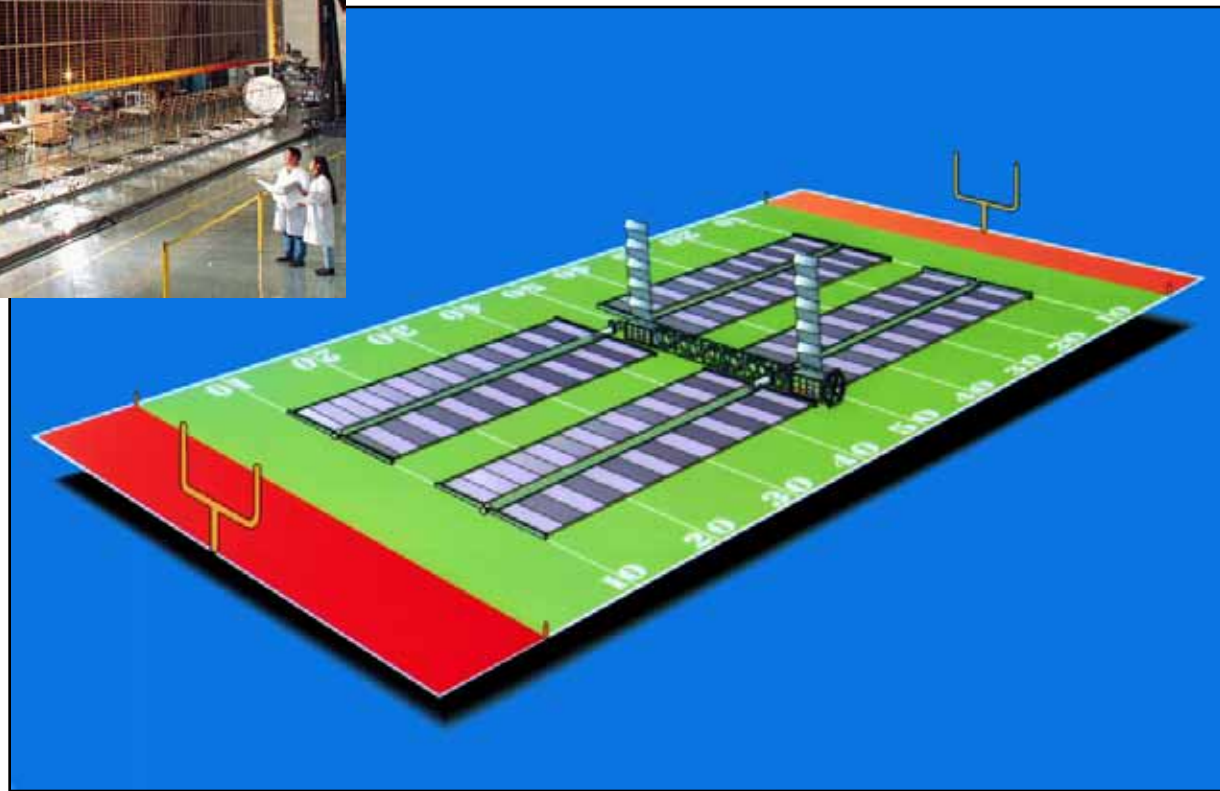
GRC was NASA lead for ISS Solar Array Development





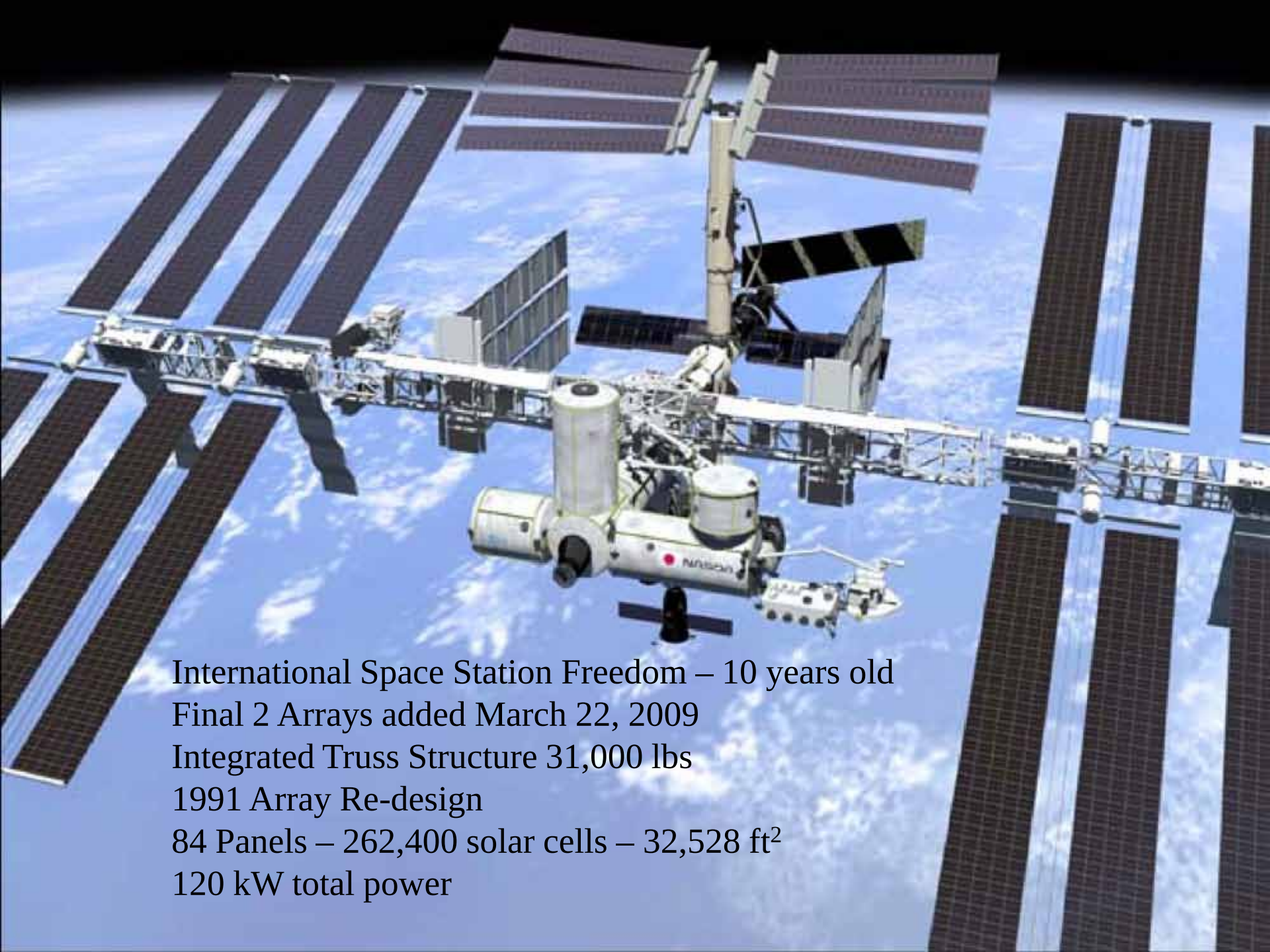
16,400 cells/blanket

262,400 cells total!

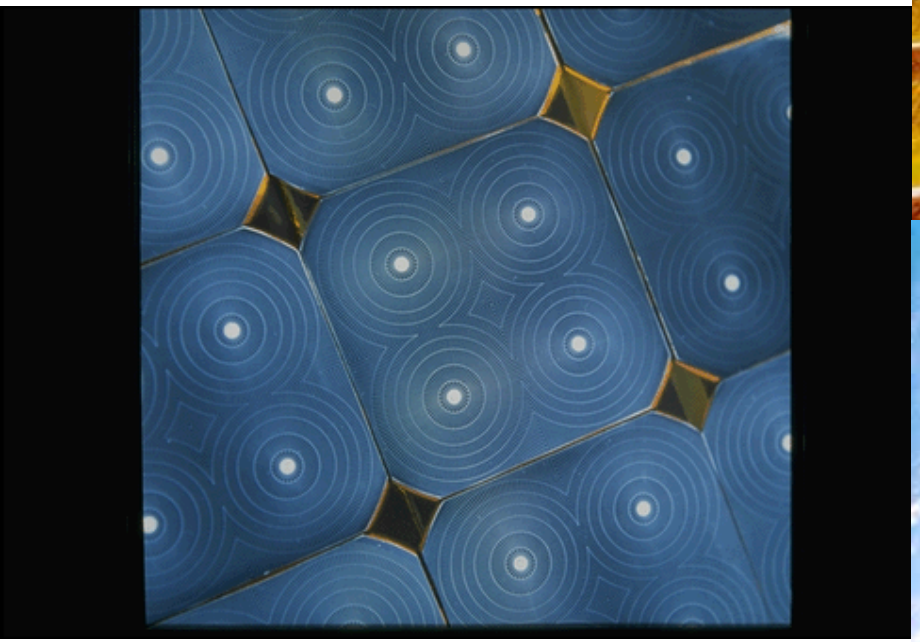


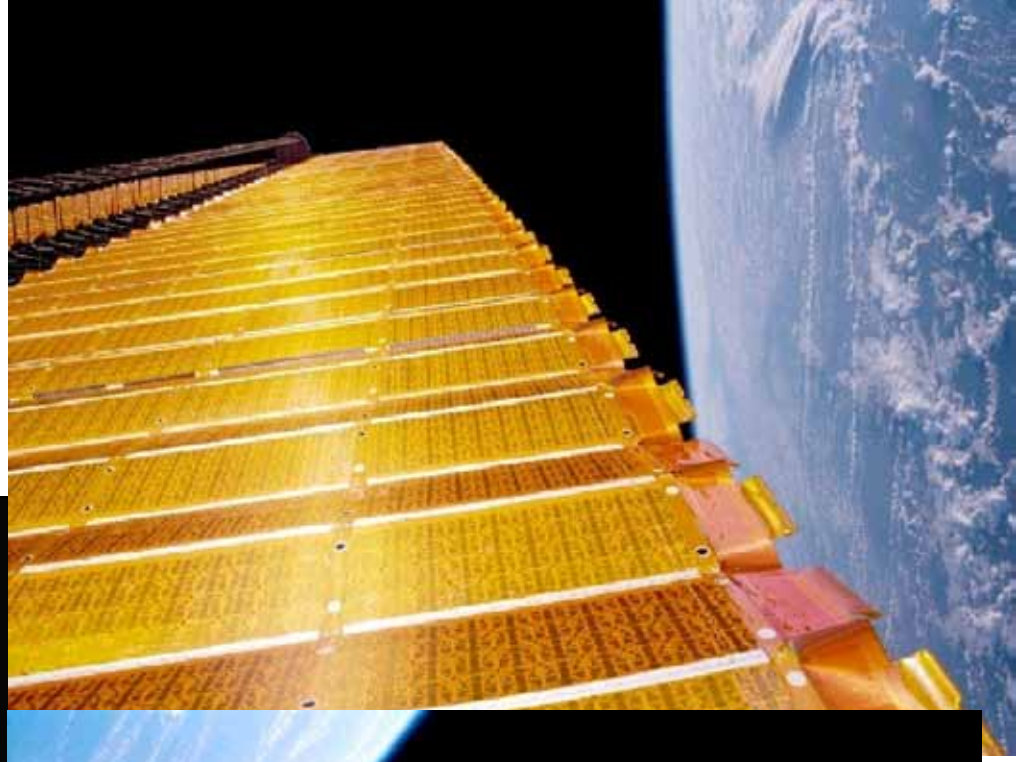
ISS Solar Arrays are built by Boeing under Contract to NASA JSC

ISS Solar Arrays are largest Solar Arrays ever deployed in space

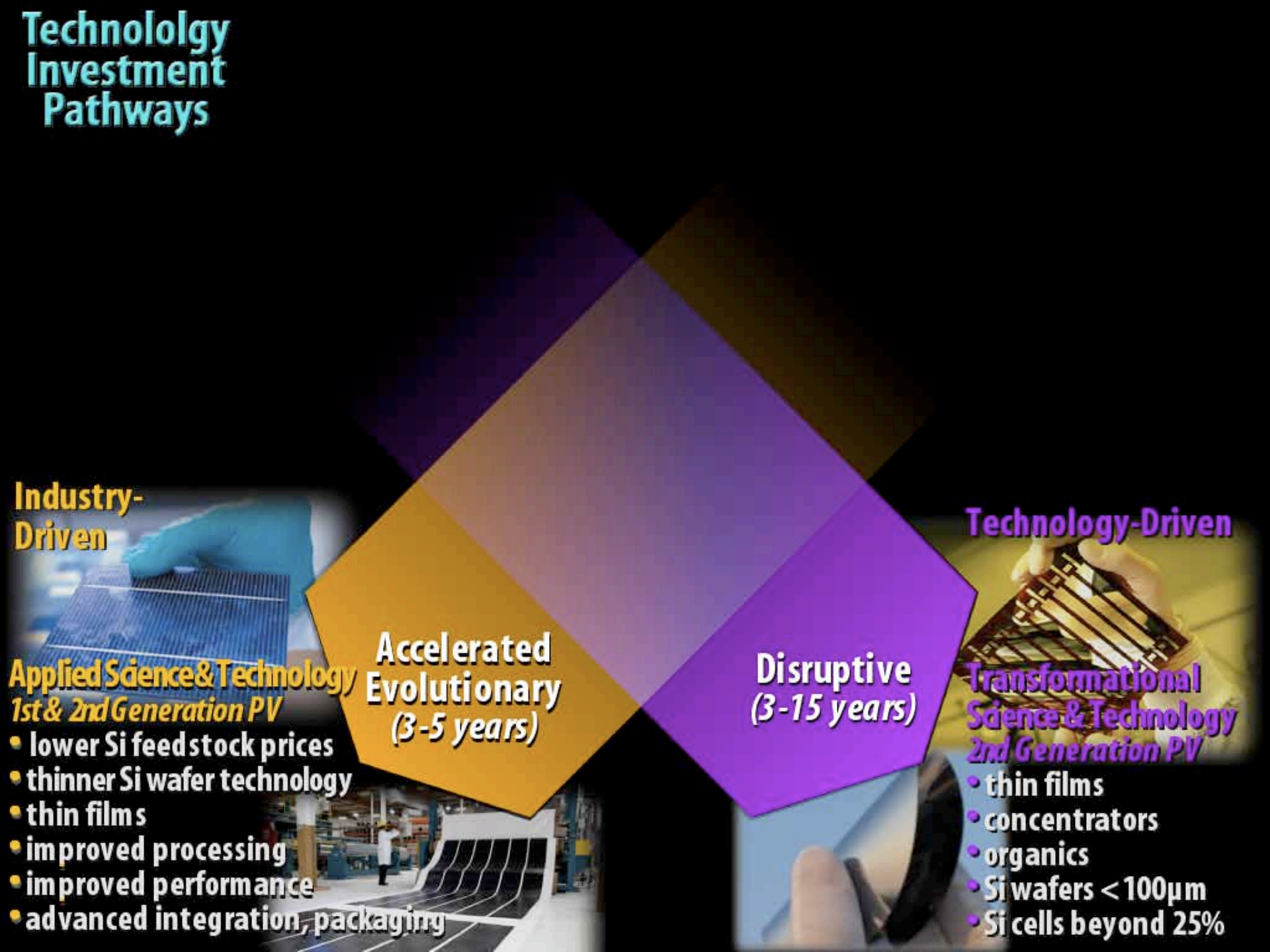


International Space Station Freedom – 10 years old
Final 2 Arrays added March 22, 2009
Integrated Truss Structure 31,000 lbs
1991 Array Re-design
84 Panels – 262,400 solar cells – 32,528 ft^2
120 kW total power



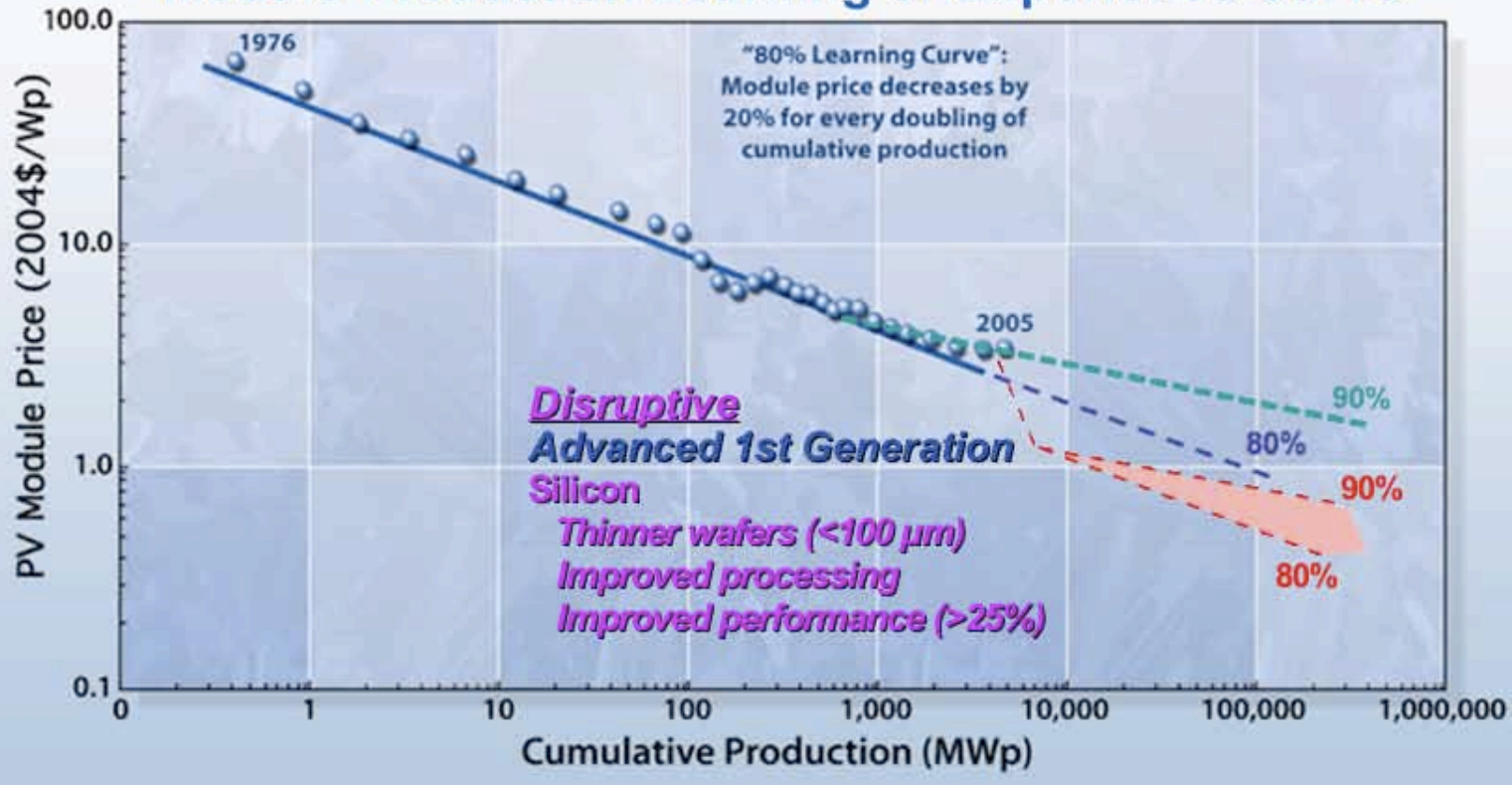


Technololgy Investment Pathways



Technololgy Investment Pathways

Module Production Learning or Experience Curve



Industry-Driven

Applied Science & Technology
1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

Accelerated Evolutionary
(3-5 years)

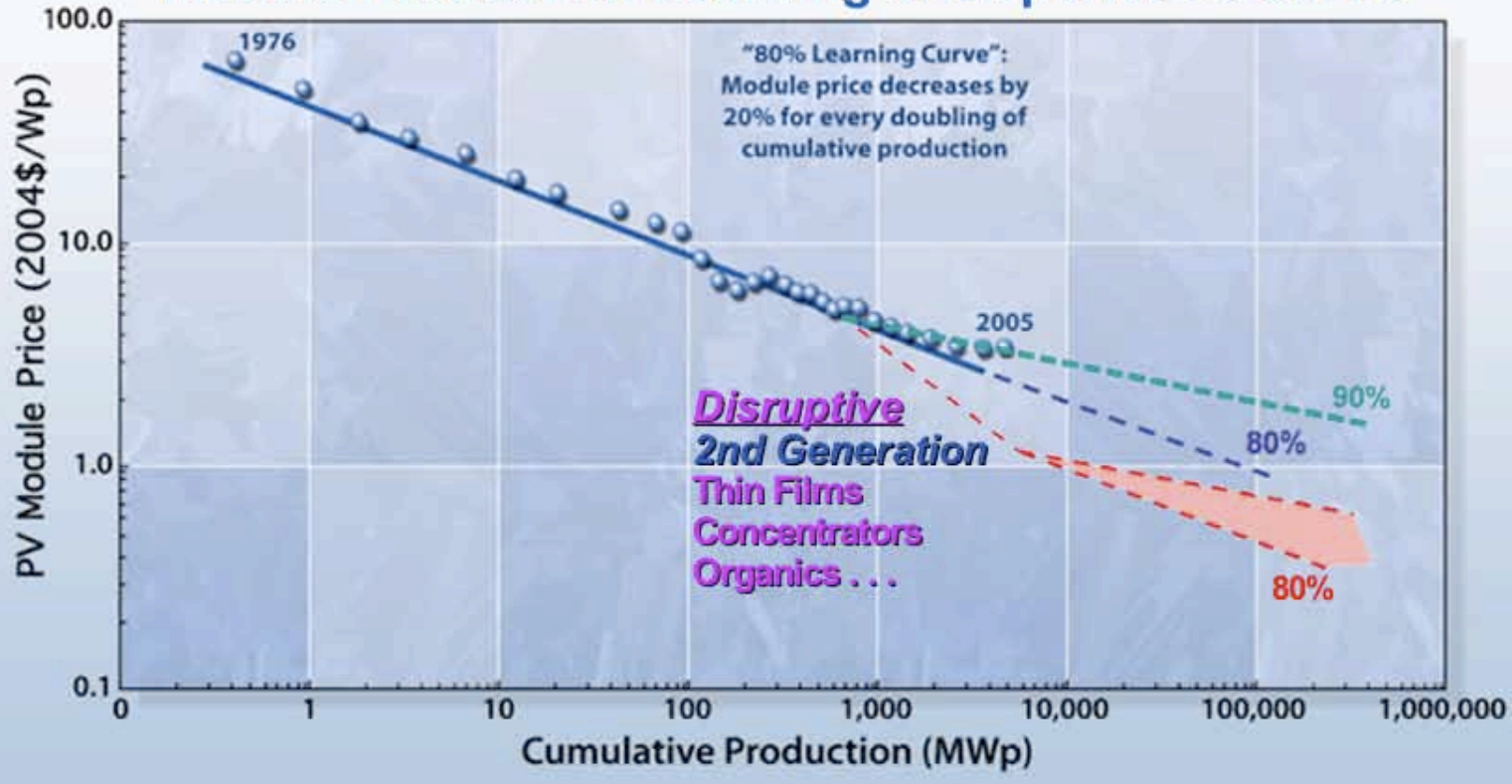
Disruptive
(3-15 years)

Transformational Science & Technology
2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%

Technololgy Investment Pathways

Module Production Learning or Experience Curve



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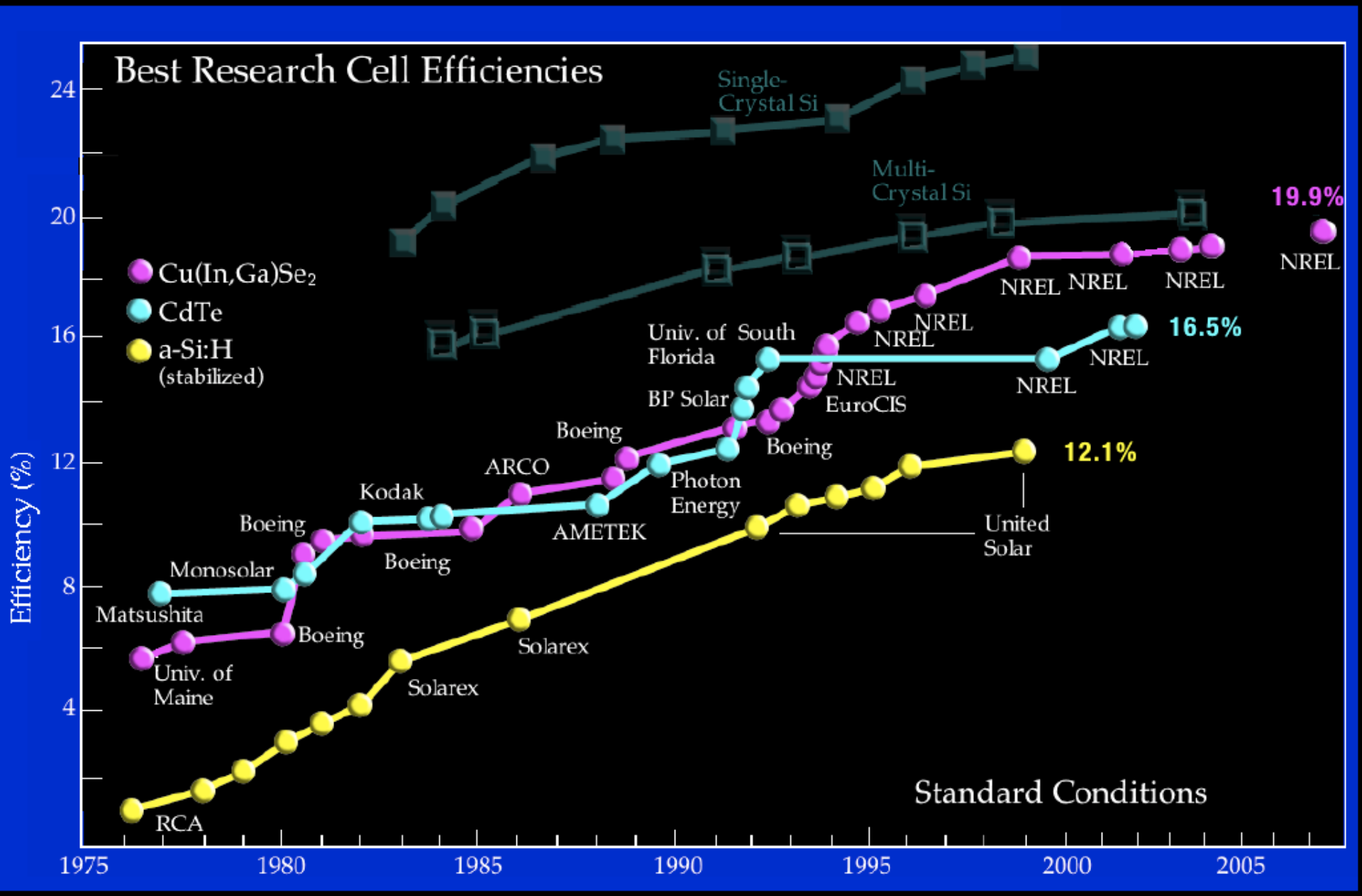
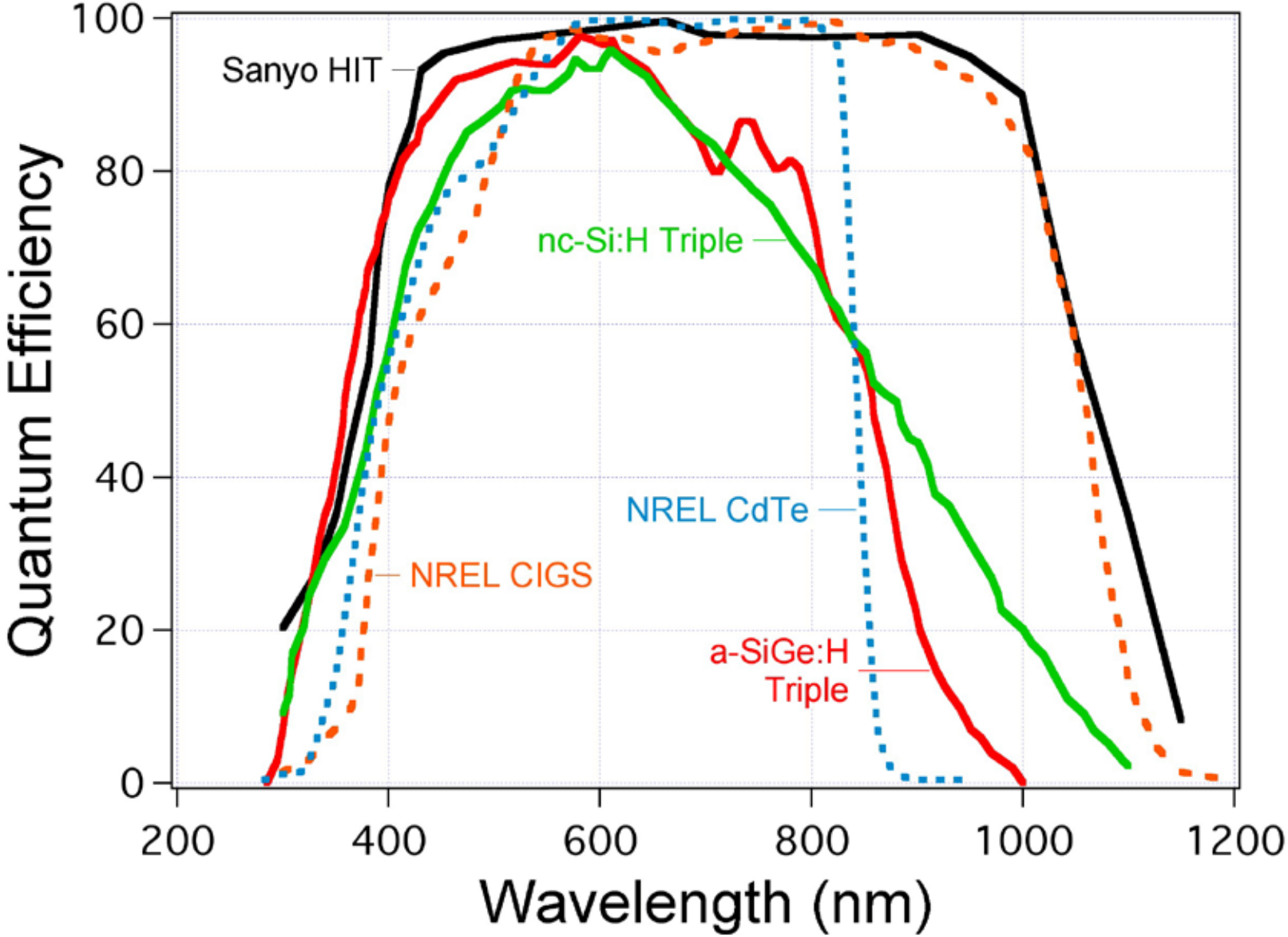
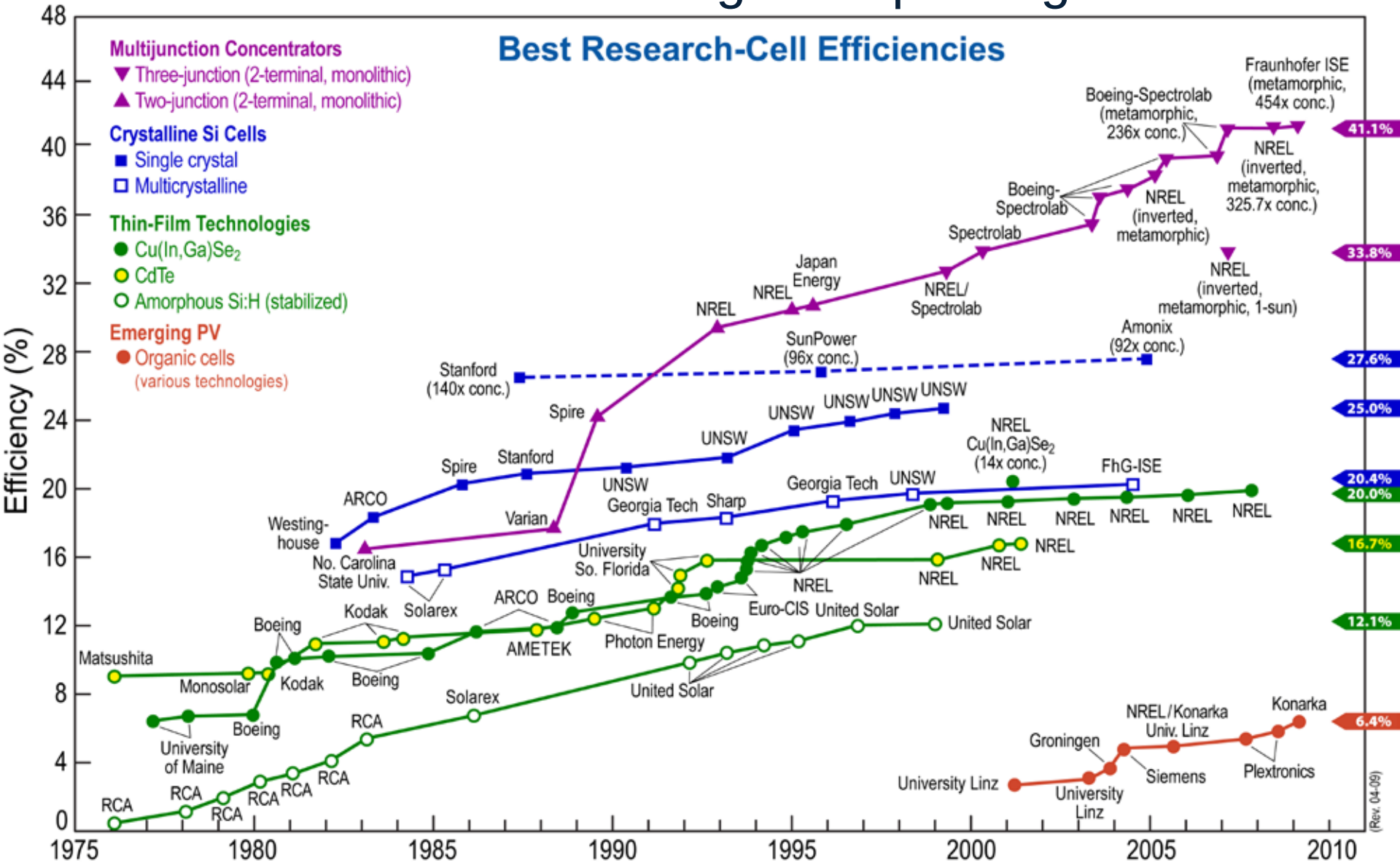

Best Research Cell Efficiencies
Single-Crystal Si
Multi-Crystal Si
Cu(In,Ga)Se2
CdTe
a-Si:H (stabilized)
19.9%
16.5%
12.1%
NREL
Univ. of Florida
South
BP Solar
EuroCIS
Boeing
ARCO
Kodak
Photon Energy
AMETEK
United Solar
Monosolar
Matsushita
Univ. of Maine
Solarex
RCA
Standard Conditions
Efficiency (%)
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005

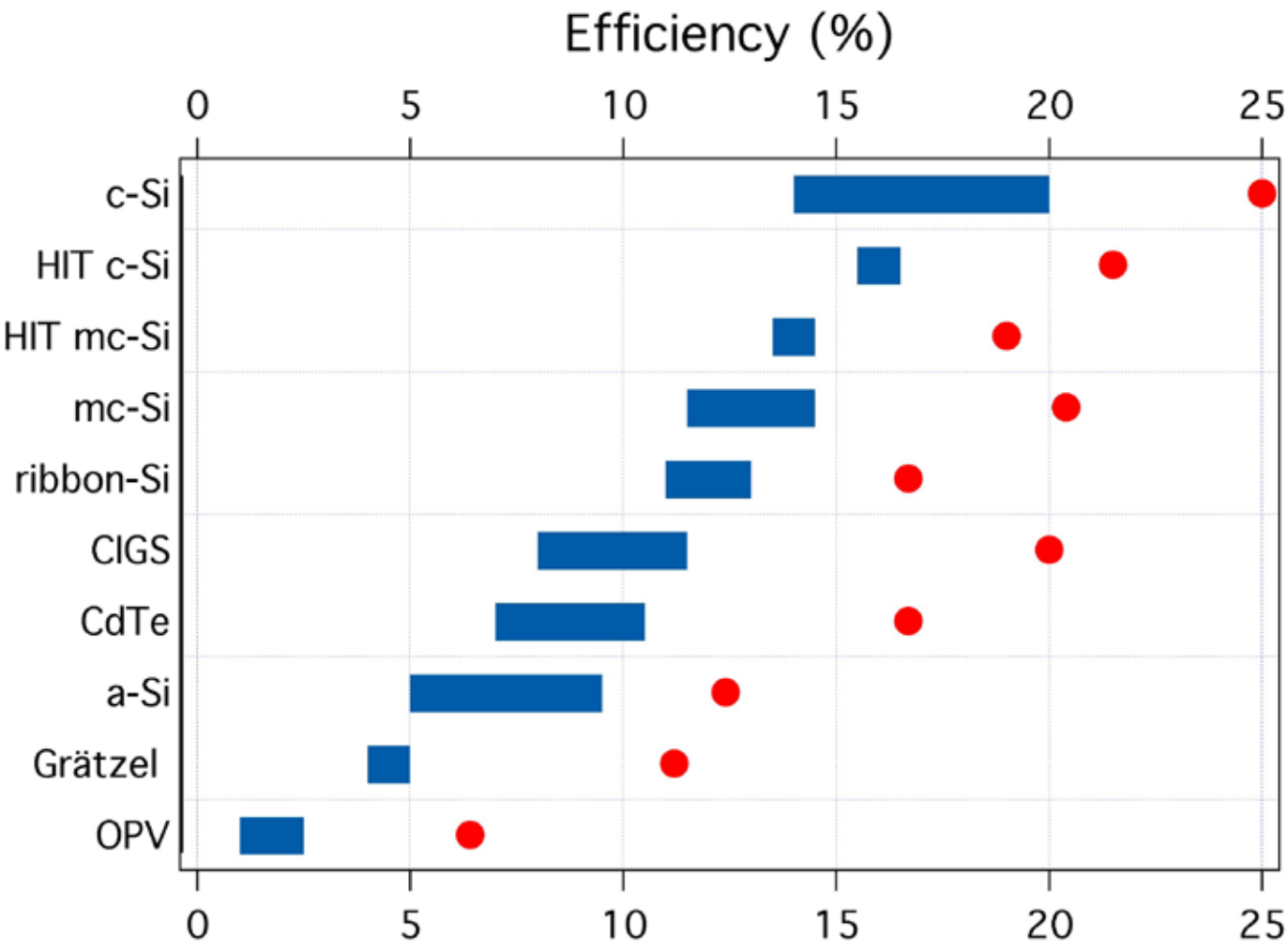
Best of Kind QE



All PV Technologies Improving

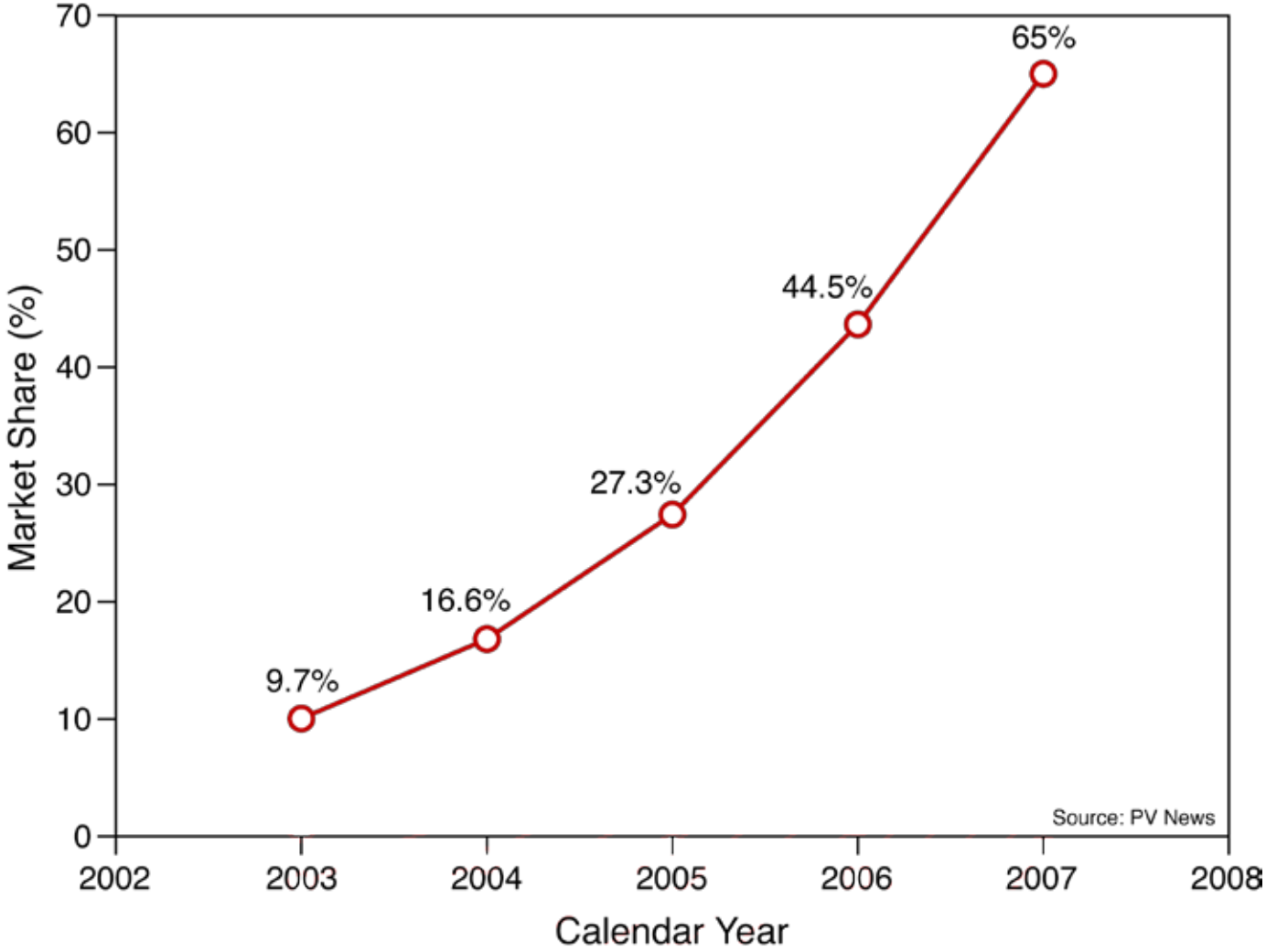


Flat Panel PV Modules & Cells



From Citigroup Global Markets, equity research,
Applied Materials, Inc, (AMT), 19 Feb. 2008

U.S. Thin-Film PV Market Share



Ref: 'Overview and Challenges of Thin Film Solar Electric Technologies', Harin S. Ullal, Ph.D., NREL 2008

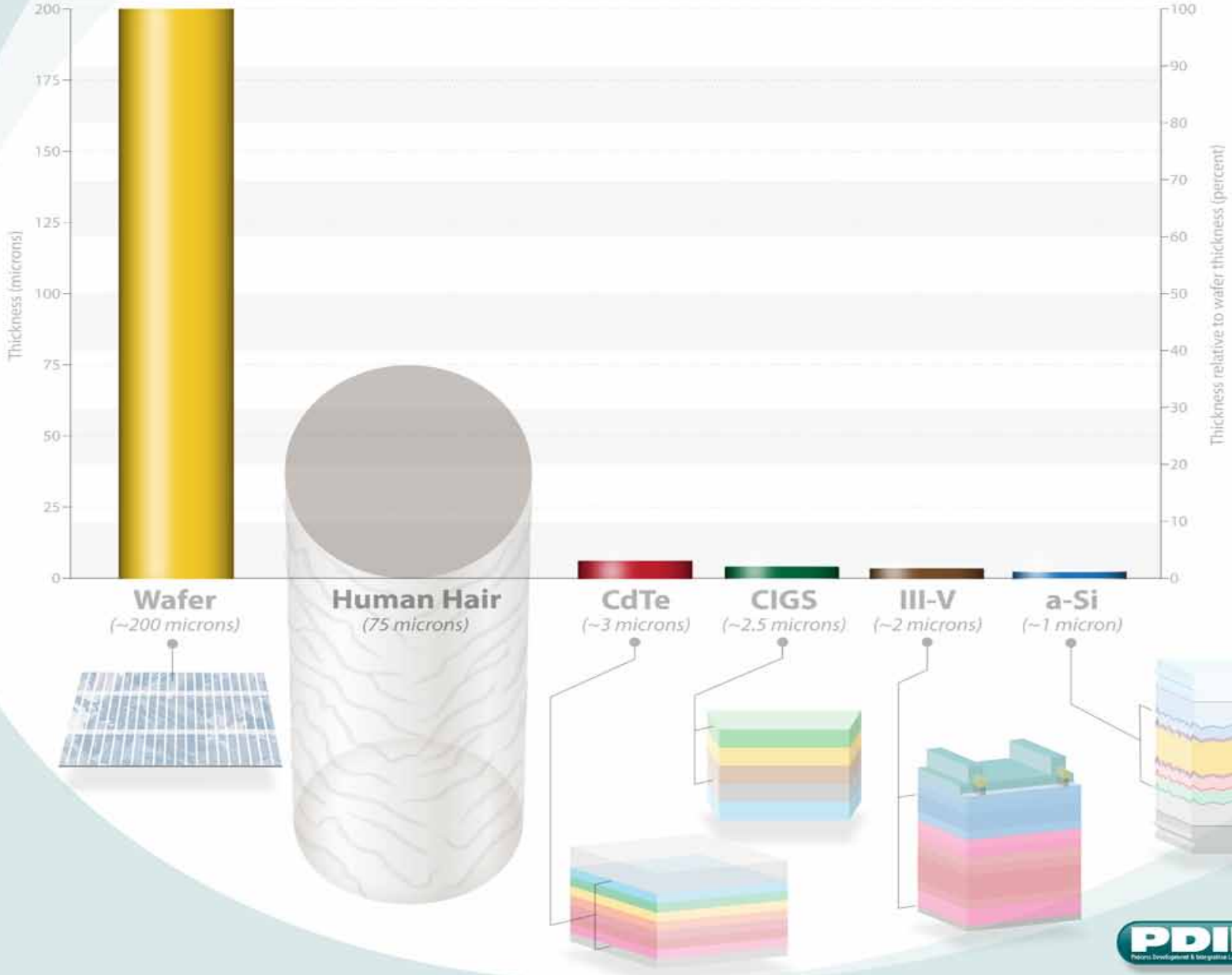
Comparing the 2008 Industry

- Thin films production is challenging. Why?
  - Less well known material systems
  - No established industry to “borrow” equipment from
  - New product customer acceptance barriers
- c-Si is more common: Why?
  - Existing equipment
  - Large knowledge base
  - Several segments of the market to enter
    - Wafer
    - Cell
    - Module
- VHS Vs Beta

Cost Advantages

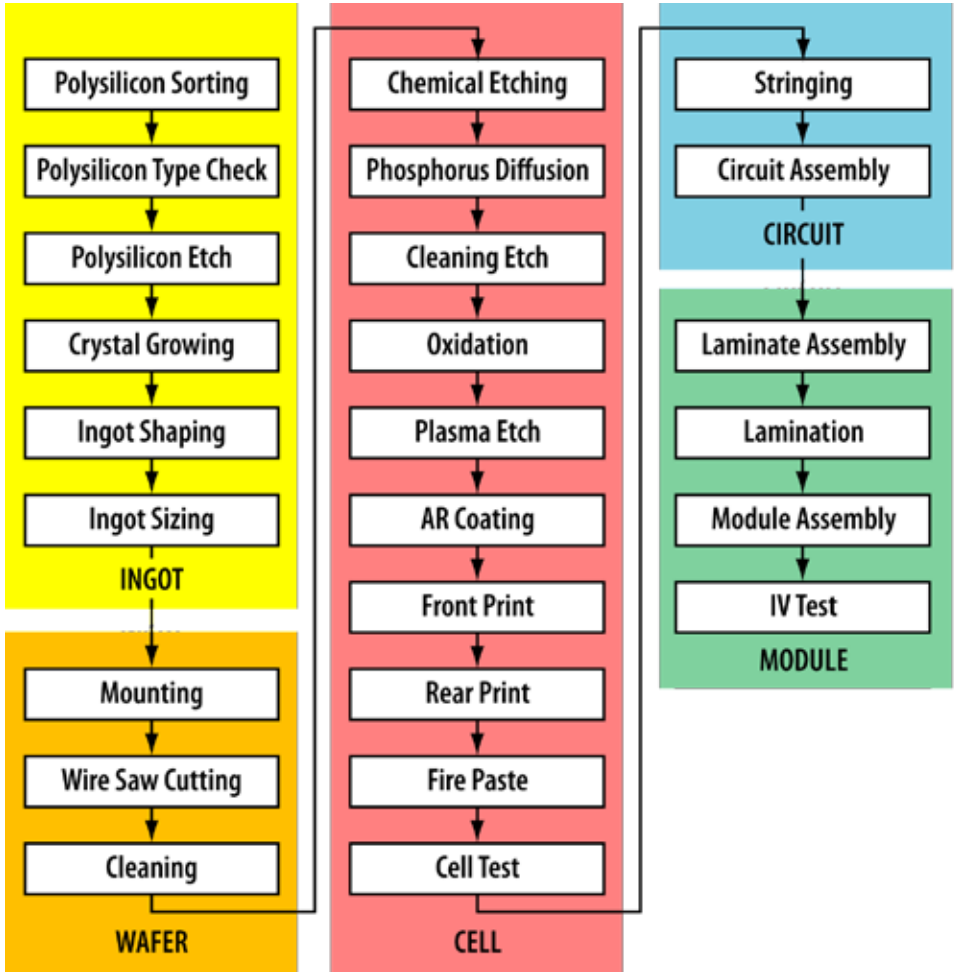
- III-V materials have the highest efficiency, but also the high cost (concentrators).
- Thin film have low efficiency but possibly much lower cost in the long run.
- Crystalline Silicon has good efficiency at a moderate cost.

Thin Films Are Really THIN

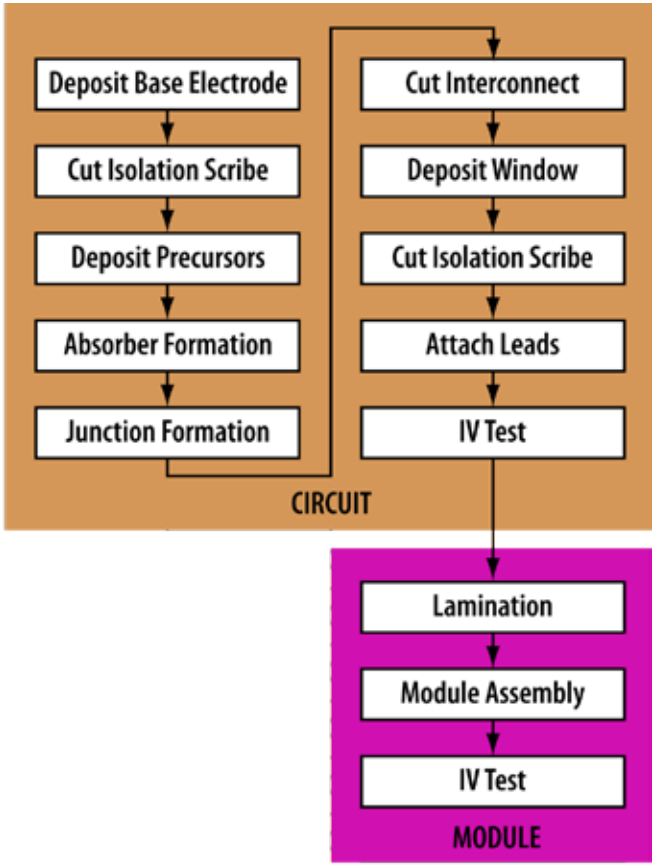


Fewer Steps, Potential Lower Cost

Crystalline Silicon Modules

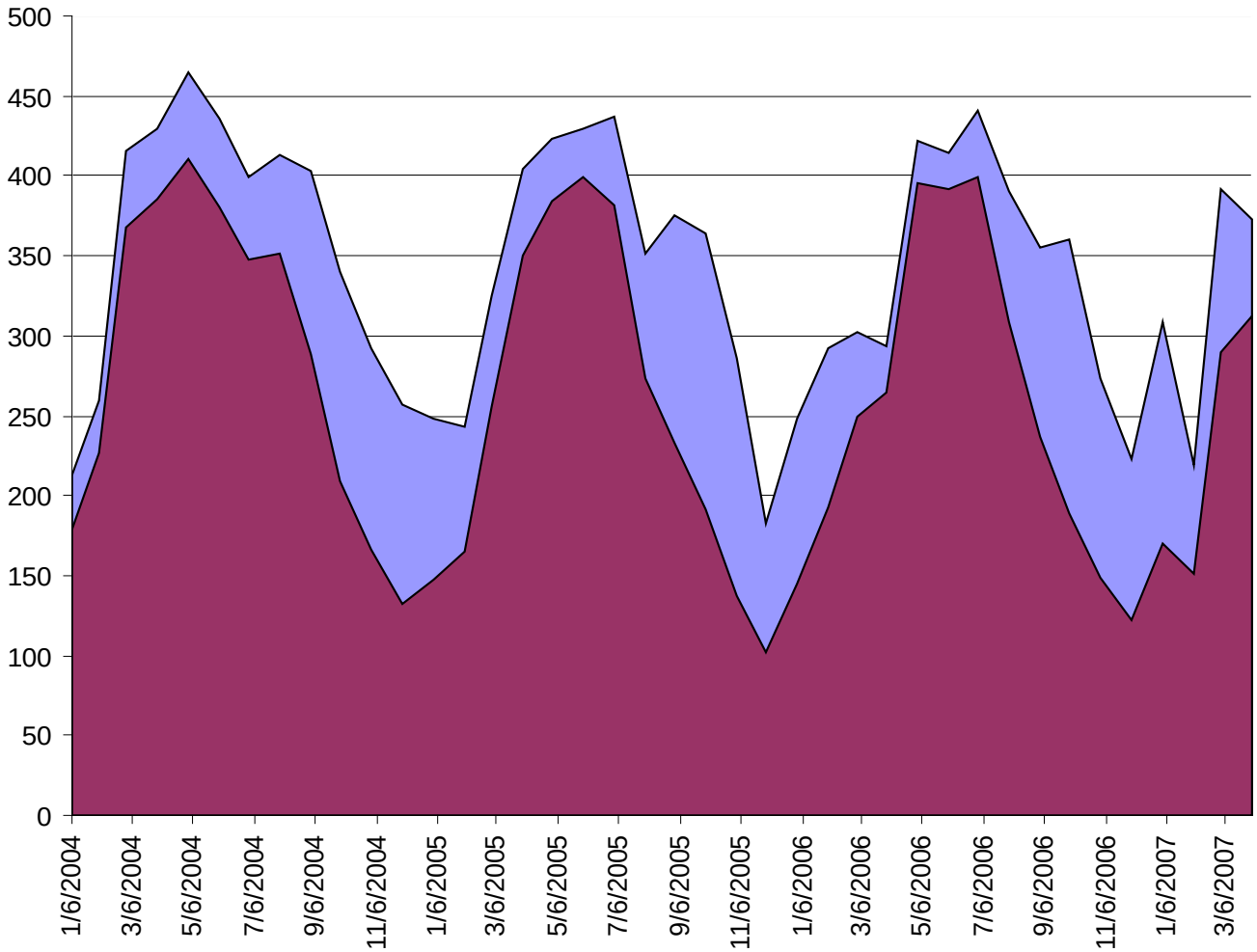


Thin Film Modules



Ref: 'Overview and Challenges of Thin Film Solar Electric Technologies', Harin S. Ullal, Ph.D., NREL 2008

= Power Rating ≠ = Energy Out



Up to 20% more electricity than crystalline PV at same cost

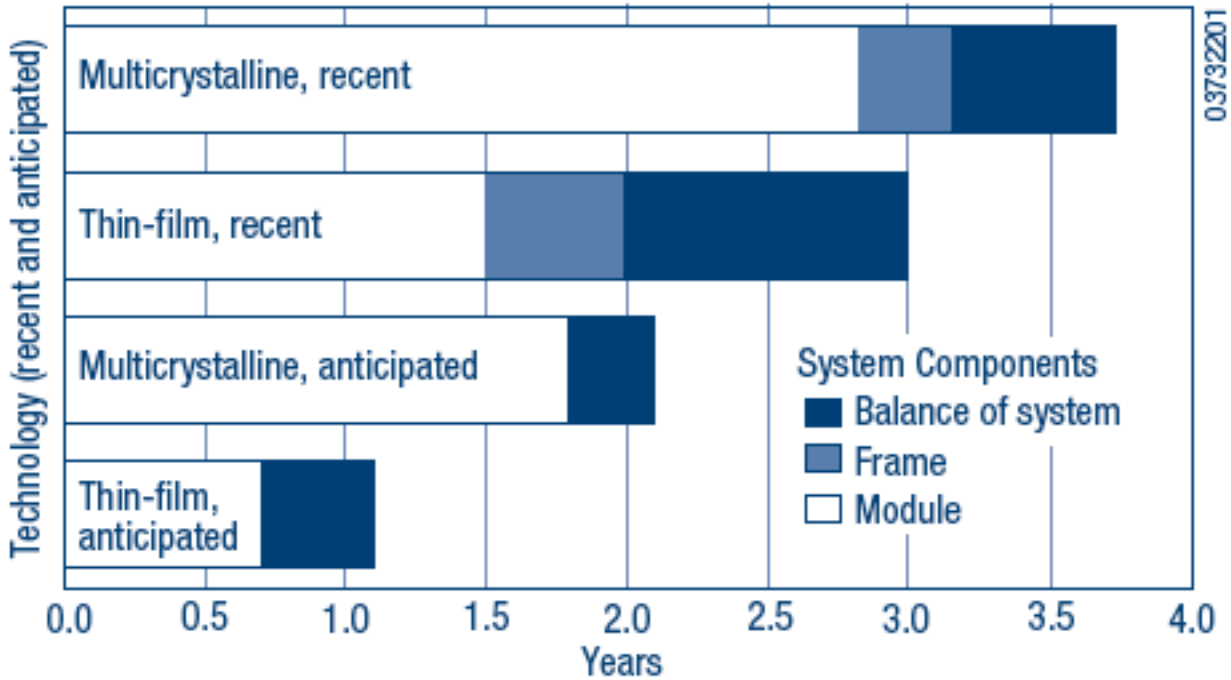
a-Si PANEL ARRAY (30°)
CRYSTALLINE PANEL ARRAY (30°))

Source: PV System Performance
Santa Cruz, CA

Ref: 'Overview and Challenges of Thin Film Solar Electric Technologies', Harin S. Ullal, Ph.D., NREL 2008

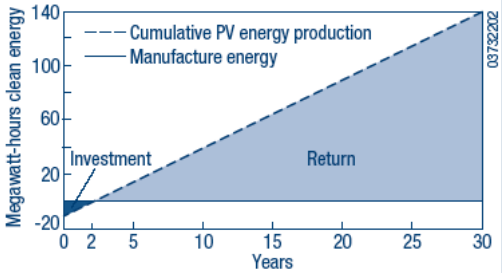
Energy Payback of PV

Figure 1. Energy Payback for PV Systems



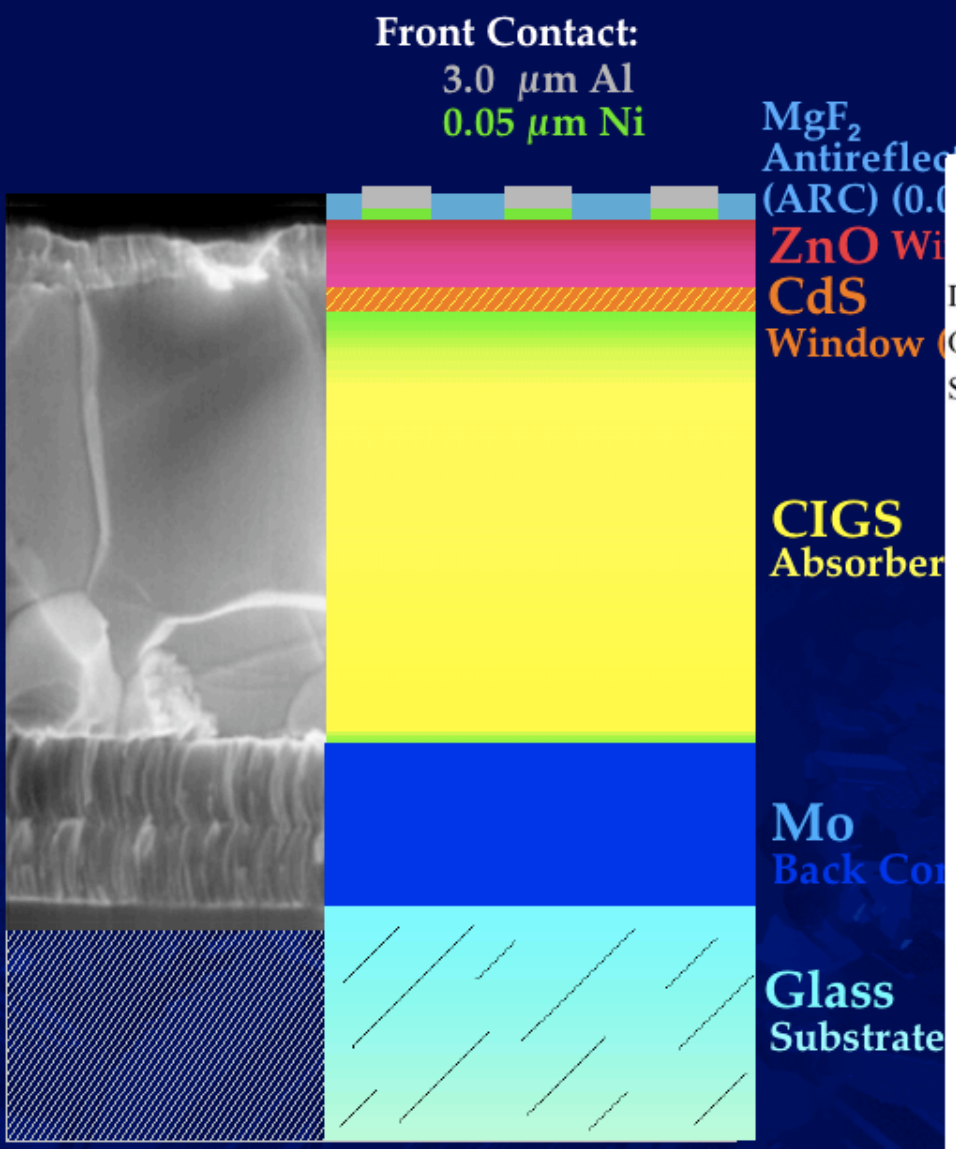
Reaping the environmental benefits of solar energy requires spending energy to make the PV system. But as this graphic shows, the investment is small. Assuming 30-year system life, PV systems will provide a net gain of 26 to 29 years of pollution-free and greenhouse-gas-free electrical generation.

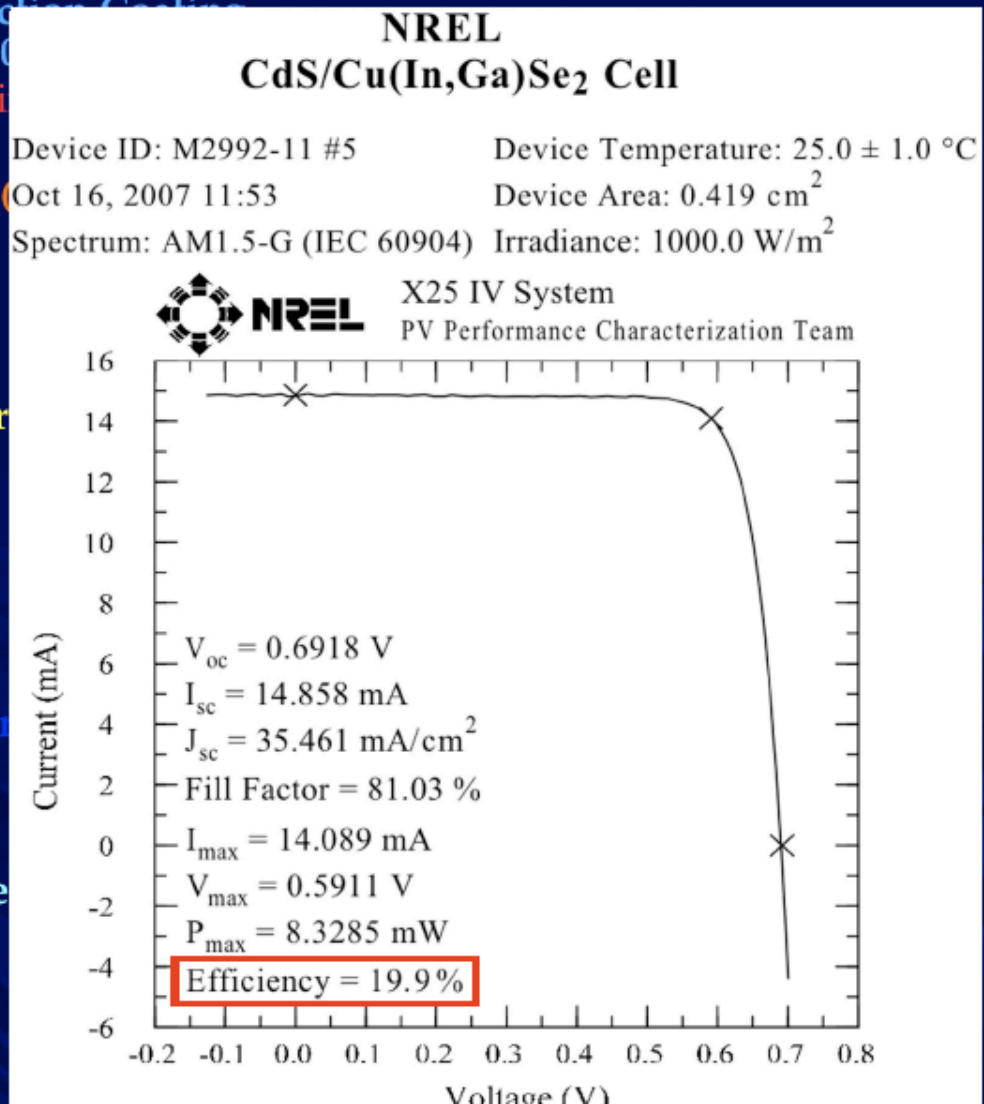
Figure 2. Cumulative Net Clean Energy Payoff



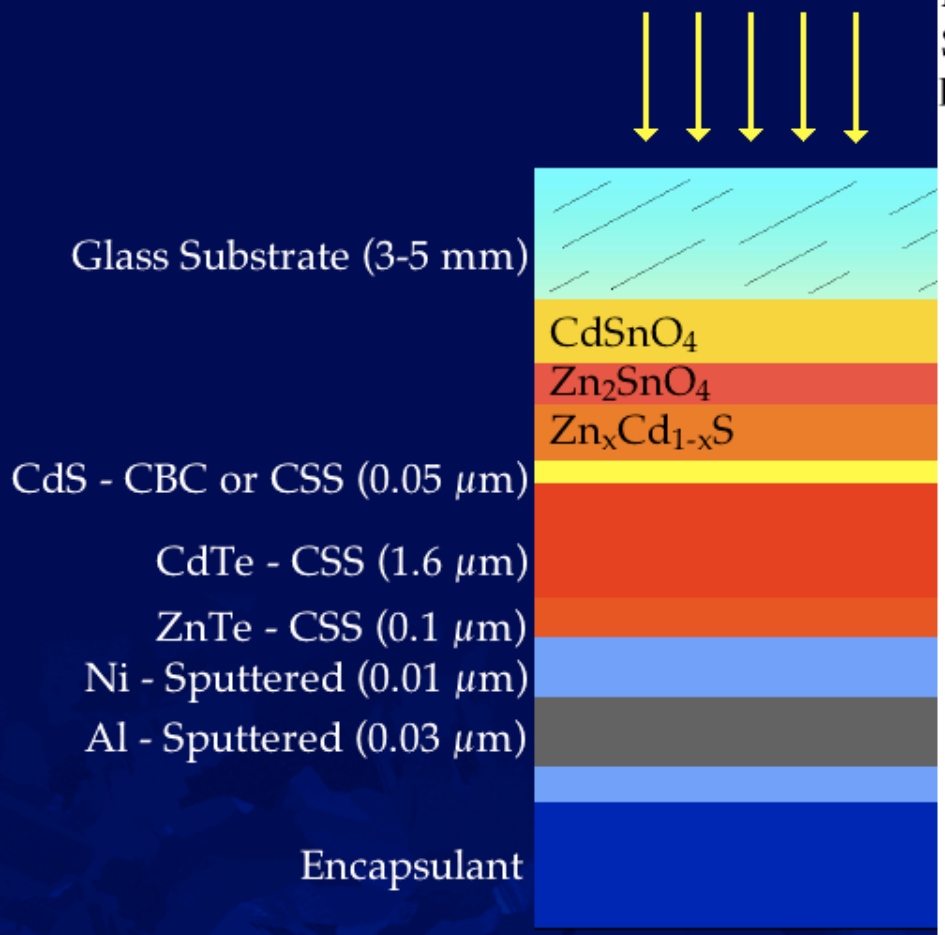
PV systems can repay their energy investment in about 2 years. During its 28 remaining years of assumed operation, a PV system that meets half of an average household's electrical use would eliminate half a ton of sulfur dioxide and one-third of a ton of nitrogen-oxides pollution. The carbon-dioxide emissions avoided would offset the operation of two cars for those 28 years.

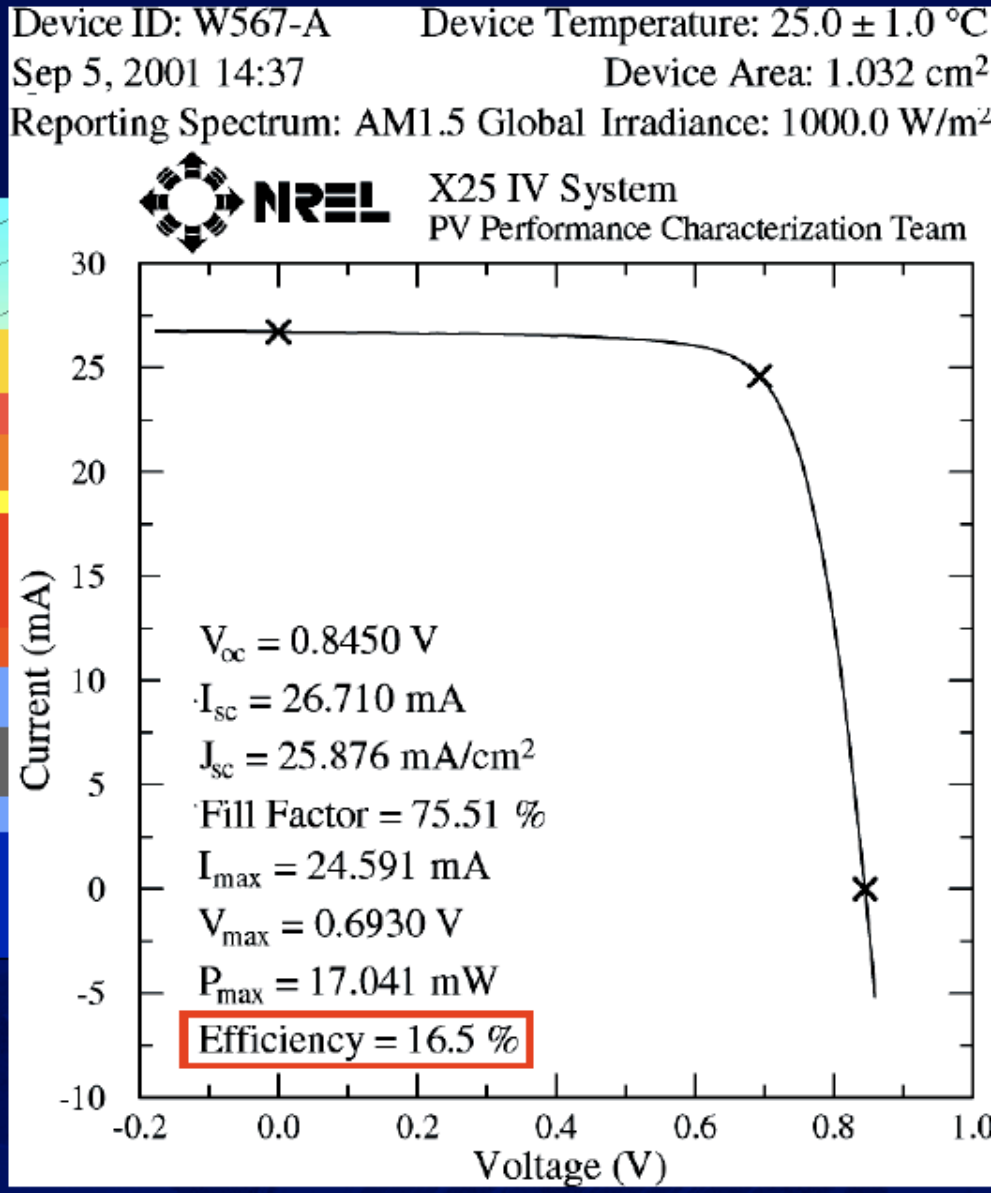
Thin-Film $Cu(In,Ga)(S,Se)_2$ - CIGSSe





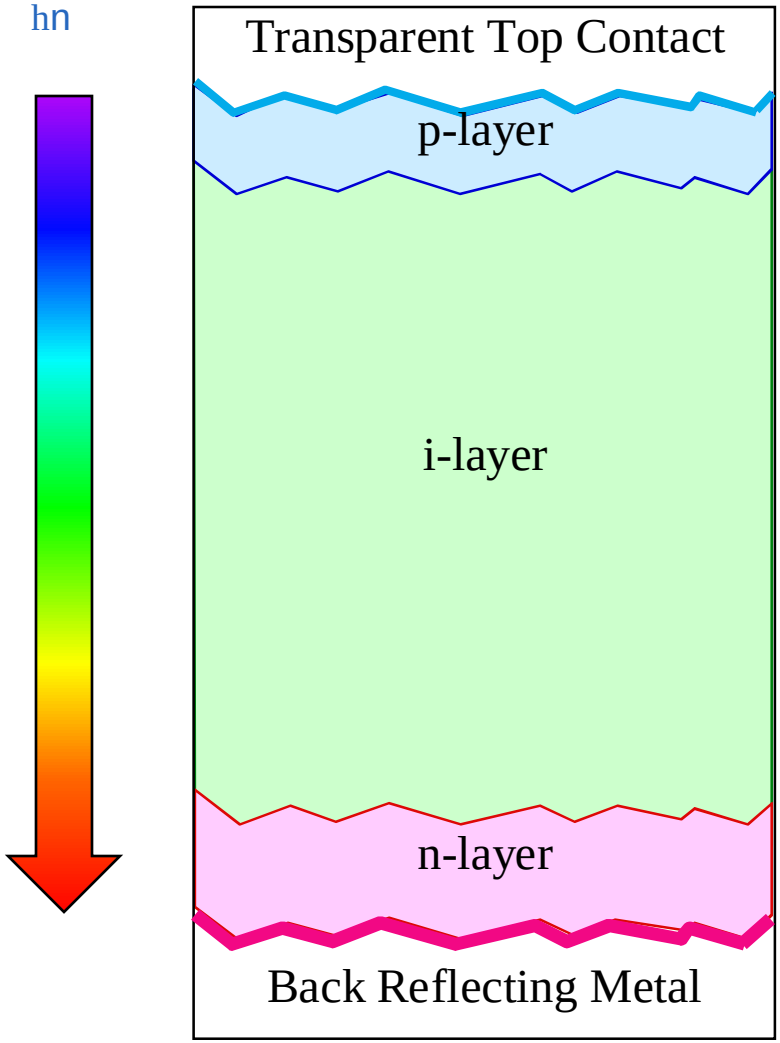
Thin-Film CdTe





Single-Junction Device Structure
Amorphous Si

- p-layer
  - 80 - 200 Å
  - wide bandgap (E_g)
  - boron doped (B_2H_6, BF_3)
- i-layer
  - 2000 - 5000 Å
  - E_g = 1.68 - 1.75 eV
  - low H_2 dilution é E_g
  - high H_2 dilution è nc-Si
- n-layer
  - 200 - 400 Å
  - phosphorous doped (PH_3)

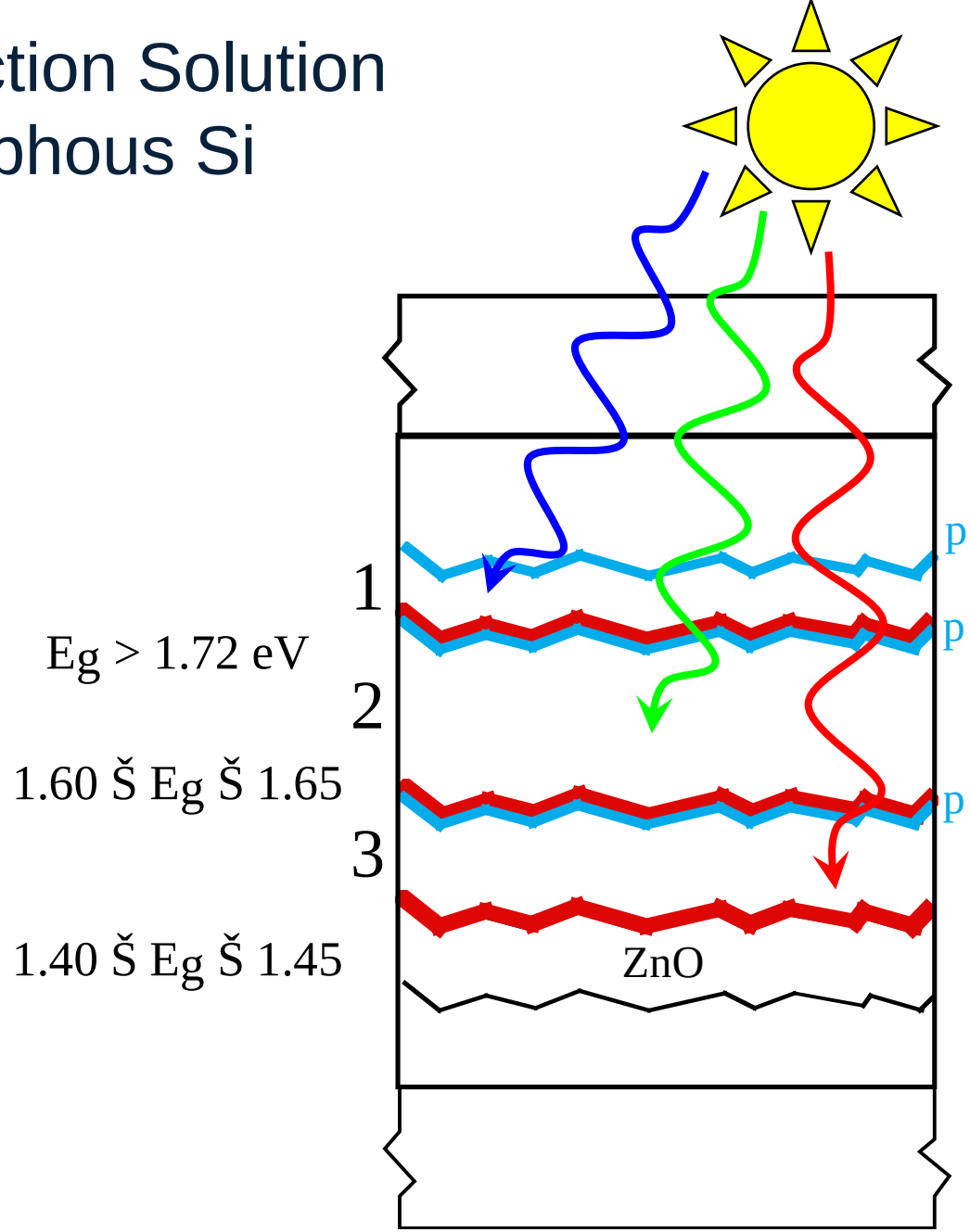


Multi-Junction Solution
Amorphous Si

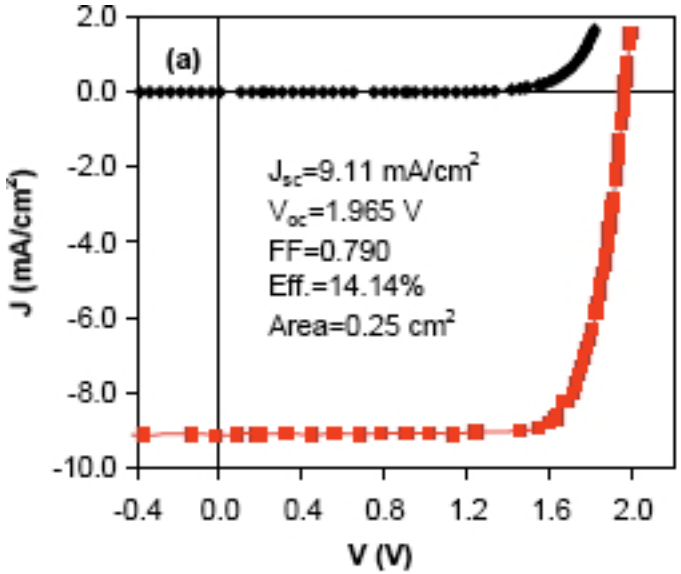
Three individual
n-i-p stacked cells.

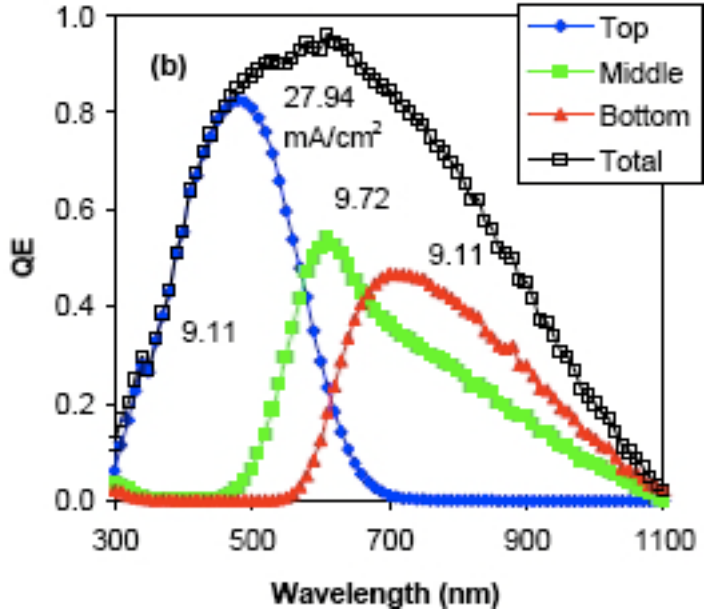
Different bandgaps
capture different
portions of the
solar spectra.

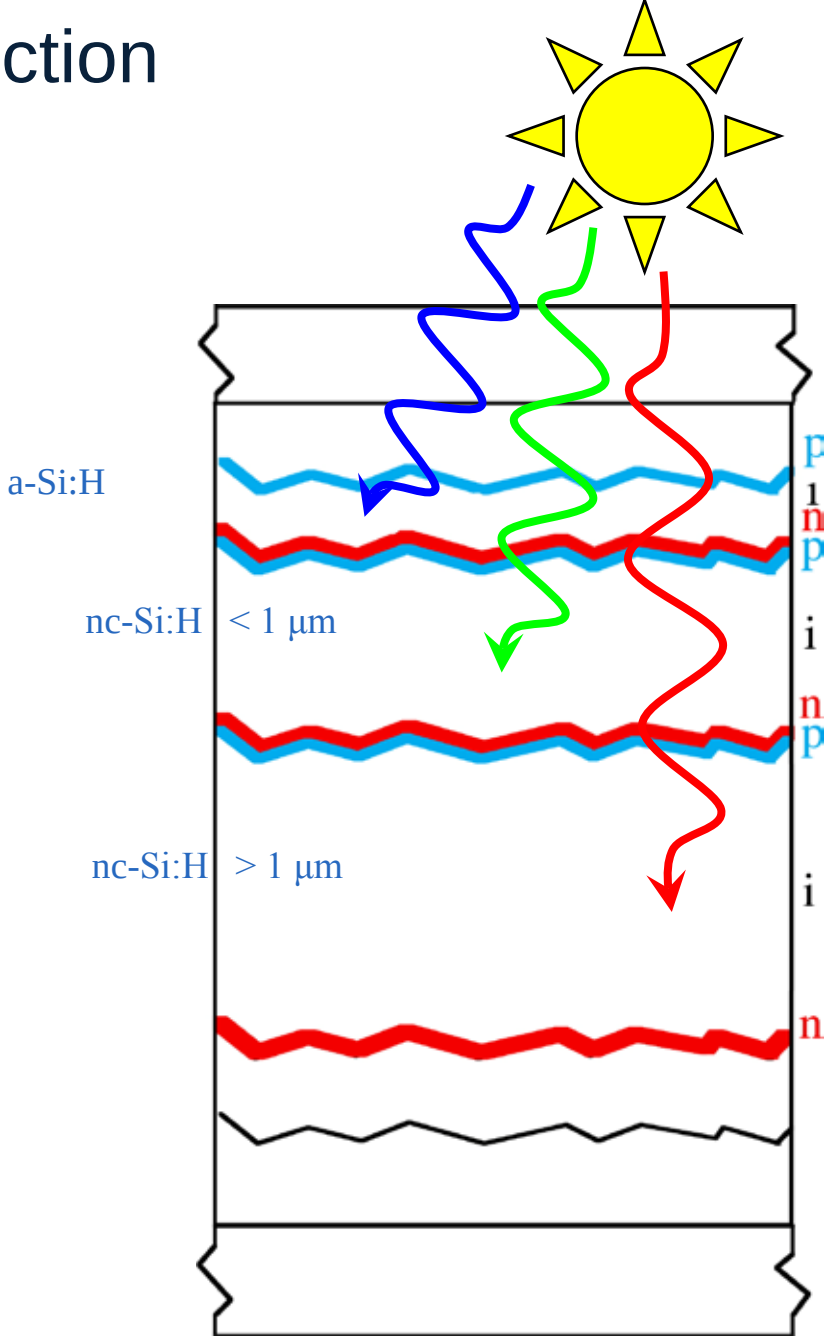
Thinner absorbers
are more stable.



nc-Si:H Multi-Junction





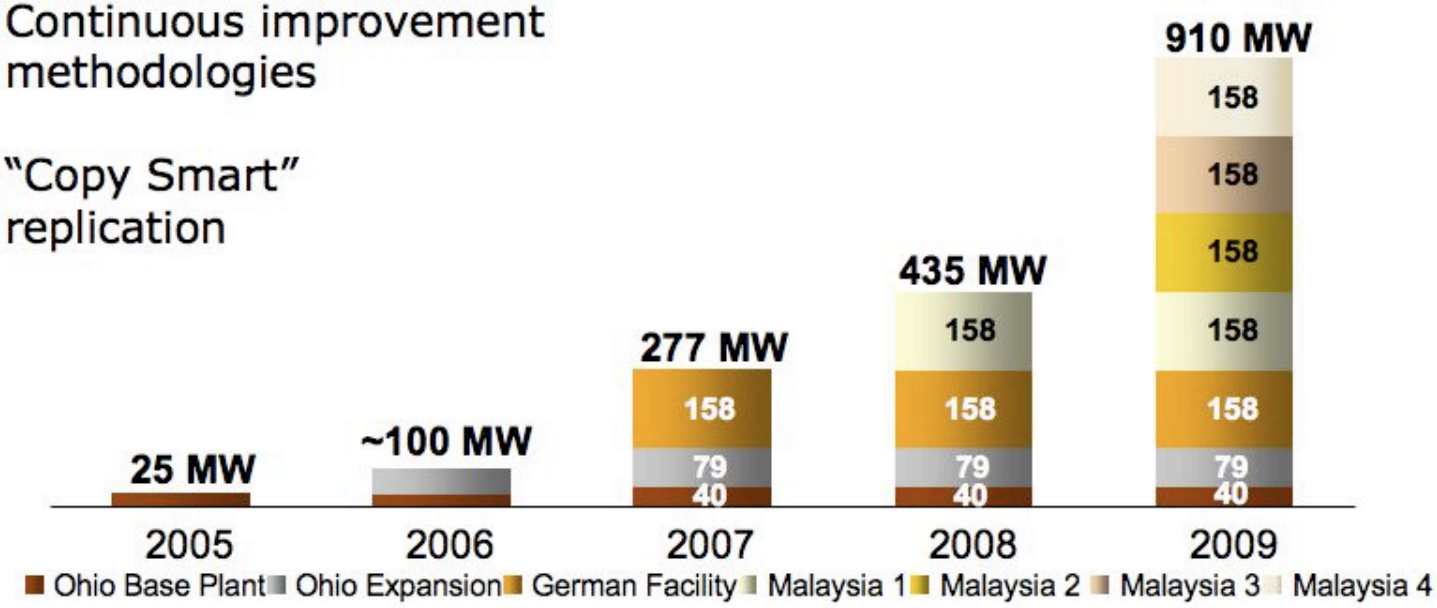


Technology & Manufacturing

First Solar.

Disciplined Replication Process

- Proven replication at Base Plant
- Continuous improvement methodologies
- "Copy Smart" replication



Thin-Film PV Companies (USA)

a-Si/Thin-Si

Uni-Solar – MI
Applied Materials – CA
Power Films – IA
Energy PV – NJ
MV Systems – CO
XsunX – CA
OptiSolar – CA
Signet Solar – CA
Nano PV – NJ
MWOE Solar – OH
Proto Flex – CO
New Solar Ventures – NM
Innovalight – CA
Nanogram – CA
Soltaix – CA
Xunlight Corp. - OH

CdTe

First Solar – OH
PrimeStar Solar – CO
AVA Solar – CO
Solar Fields – OH
Canrom – NY
Ascentool – CA
Nuvo Solar Energy – CO
Zia Watt Solar – TX
Solexant – CA
Bloo Solar – CA

Organic

Konarka – MA
Plextronix – PA
GPEC – NJ
LumoFlex – GA
MicroFab – TX
Luna Innovations – VA

CIS

Global Solar – AZ
Miasole – CA
Energy PV – NJ
Ascent Solar – CO
ISET – CA
ITN/ES – CO
Daystar – NY
Nanosolar – CA
Heliovolt – TX
Solo Power – CA
Solyndra – CA
RESI – NJ
Light Solar – NV
Ampulse – TN
Stion – CA

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Applied Materials announces $1.9 billion deal for solar panels

By Matt Nauman
Mercury News
Article Launched: 03/04/2008 10:15:17 AM PST

Applied Materials, the Santa Clara chip equipm
this morning to supply $1.9 billion worth of mac
panels.

The tools will be used in factories that will manu
year. Last year, the world's solar industry produ

"It is the largest sales agreement in Applied hist

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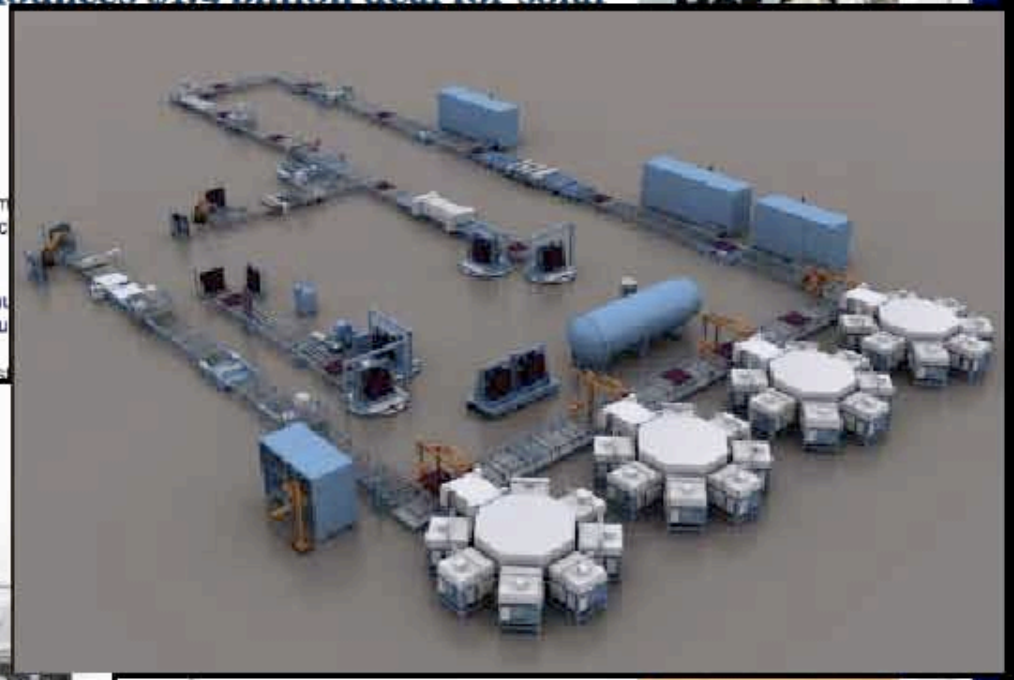
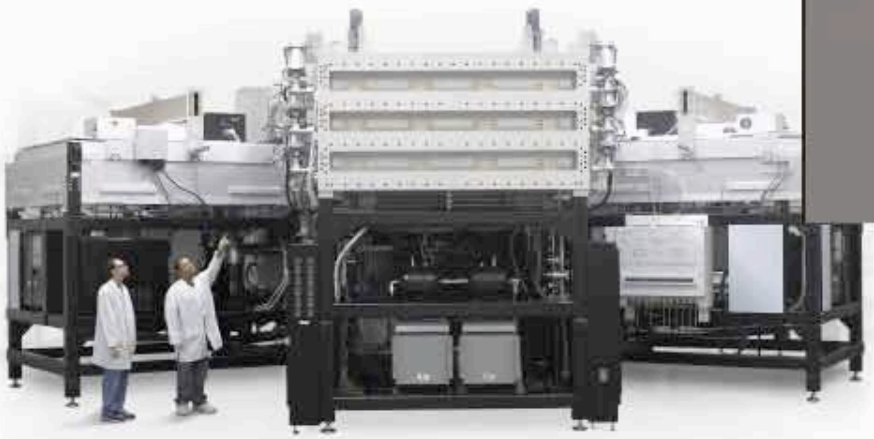


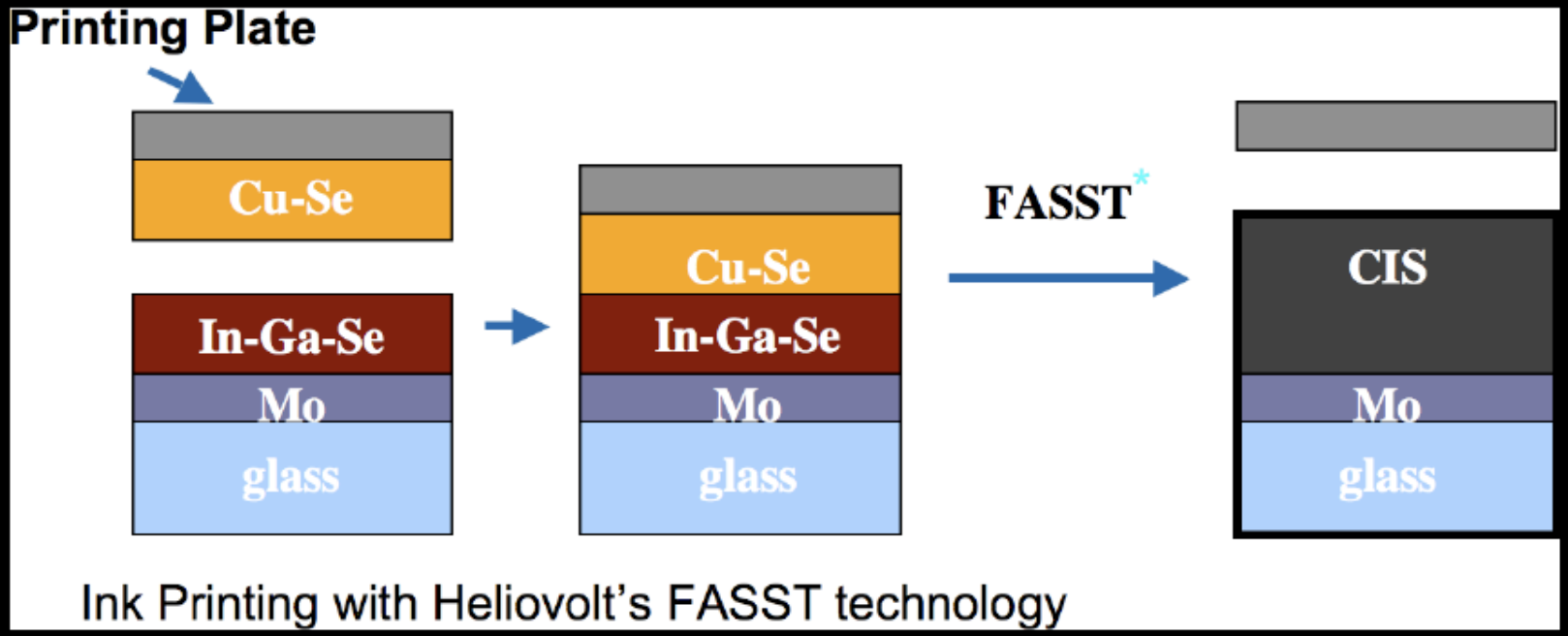


$15 million
to $46 million due to increased R&D spending on lower-cost solar equipment, amortization of recent acquisitions and marketing cost for its expanding solar business.

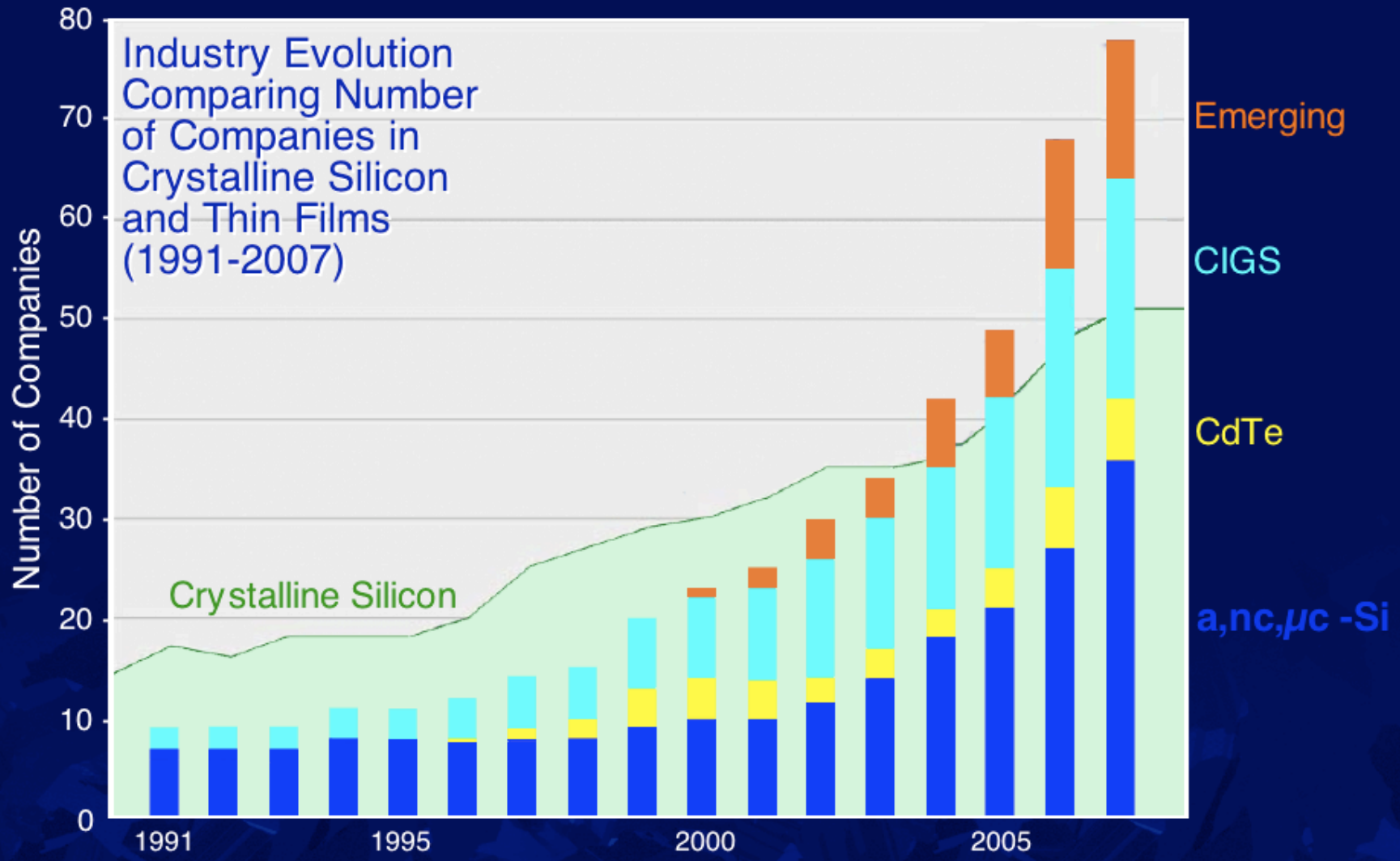
Contact Matt Nauman at mnauman@mercurynews.com or (408) 920-5701.

I HOPE the water's 30 degrees

Heliovolt

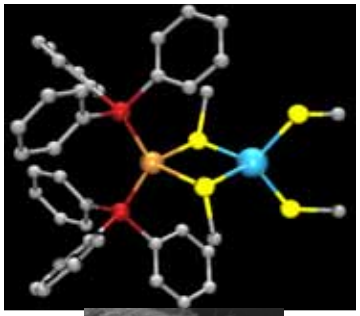


**Field-Assisted Simultaneous Sythesis and Transfer*

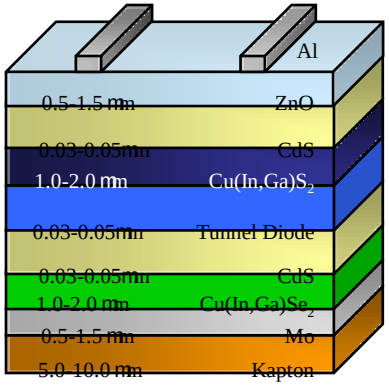

Industry Evolution
Comparing Number
of Companies in
Crystalline Silicon
and Thin Films
(1991-2007)
Number of Companies
80
70
60
50
40
30
20
10
0
1991
1995
2000
2005
Crystalline Silicon
Emerging
CIGS
CdTe
a,nc,μc -Si

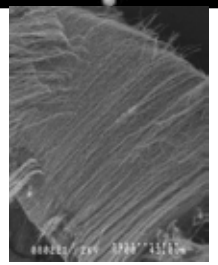
Advanced Thin Film Technology

Dr. Aloysius F. Hepp, Jeremiah S. McNatt and Dr. John E. Dickman
National Aeronautics and Space Administration,
John H. Glenn Research Center, Cleveland, OH 44135



Dr. Michael H.-C. Jin and Dr. Kulbinder K. Banger
Ohio Aerospace Institute, Brookpark, OH 44142





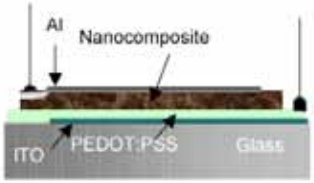
Profs. Don L. Morel and Chris S. Ferekides
EE & Comp. Eng., University of South Florida, Tampa, FL 33620

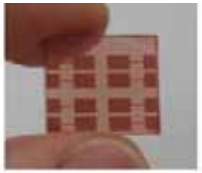
Dr. Nese Orbey and Michael Cushman
Foster-Miller, Inc., Waltham, MA 02451

Drs. Robert W. Birkmire and William N. Shafarman
Inst. for Energy Conv., University of Delaware, Newark, DE 19716

Drs. Krishna C. Mandal and Fei Wang
EIC Laboratories, Inc., Norwood, MA 02062

Prof. John R. Reynolds
Dept. of Chemistry, Univ. Florida, Gainesville, FL 32611





Prof. Sam Sun
Chemistry, Norfolk State Univ., Norfolk, VA 23504

Robert Newton
Techni-Met, Inc., Windsor, CT 06095

Advanced Thin Film Technolgoy

Ultra-Lightweight Hybrid Solar Cell Arrays for Space Power

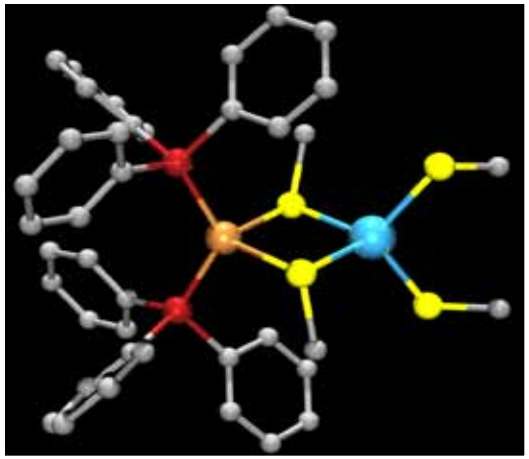
Advanced Thin Film Technologies for Ultra-lightweight Solar Cell Arrays **(Legacy)**

Advanced Manufacturing Process for Nanostructured and Quantum Dot Enhanced Photovoltaics for Exploration **(Re-vectored)**

- Single Source Precursors
- Nanomaterials
- Tandem Solar Cells
- Polymer Substrates
- Technology Foundations: Hybrid Solar Cells

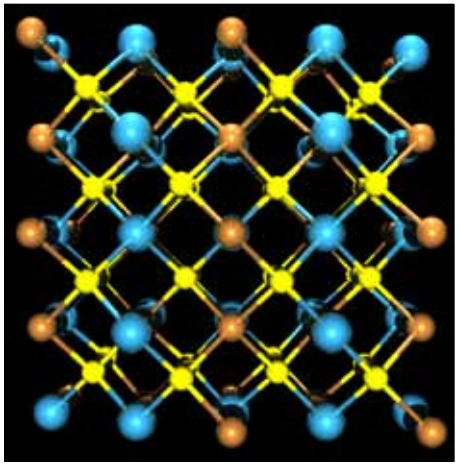
Technology Foundations: Single-Source Precursors

- Key step for thin-film solar cells is the deposition onto flexible/lightweight substrates (polyimides)
- Current methods for crystalline compounds require high temperatures which are incompatible with all known flexible polyimides
- Use of multi-source inorganic/organometallic precursors in a chemical vapor deposition (CVD) process is more appealing
- Stoichiometric control of deposited films can be difficult - alternative approach is the use of ternary single source precursors (SSP's)
- I-III-VI_2 stoichiometry is "built-in"
- Suitable for low temperature deposition
- Number of known ternary SSP's is limited, as is their use in deposition processes; ideal as precursor for nanoparticles of inorganic materials



$[\{PPh_3\}_2Cu(SEt)_2In(SEt)_2]_s$

~ 175 - 450°C

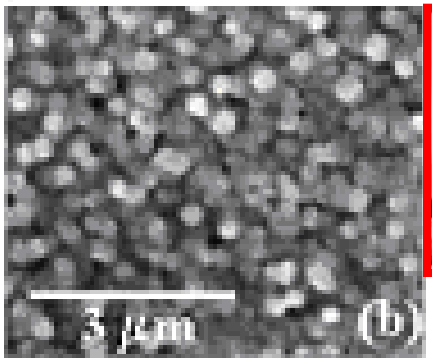


$CuInS_2$ (Chalcopyrite)

Technology Foundations: Production of Nanomaterials

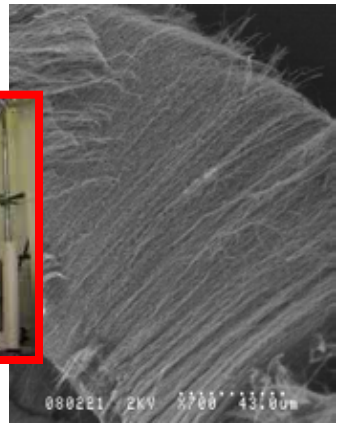
- In spray CVD a precursor is ultrasonically nebulized, and swept into a two-zone, hot-wall reactor
- The carrier solvent is evaporated in the warm zone and the gaseous precursors are decomposed in the hot zone where film growth occurs
- Spray CVD process can also be used to grow MW-CNT using “floating zone catalyst” method
- The key to producing more efficient nanocrystallites for use in nanotechnology is to design a completely new process for the synthesis of many types of nanocrystallites using computer control - intelligent manufacturing which:
  - Uses generic ultrasonic technology to fabricate capped or uncapped nanocrystallites
  - Develops a nanocrystallites synthetic process and tool that can achieve high <u>reproducibility</u>, high <u>throughput</u>, and <u>well controlled</u> size distribution

Vertical Low-P cold-wall reactor



SEM of uncapped $CuInS_2$ nano-crystallites prepared in reactor

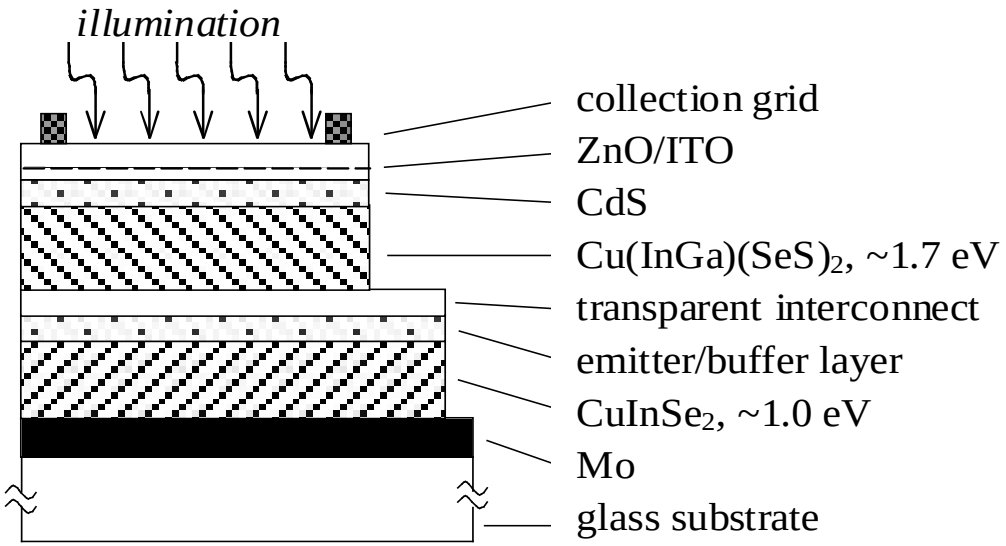
Horizontal atmospheric hot-wall reactor



Cross-sectional view of multiwalled carbon nanotubes grown via CVD

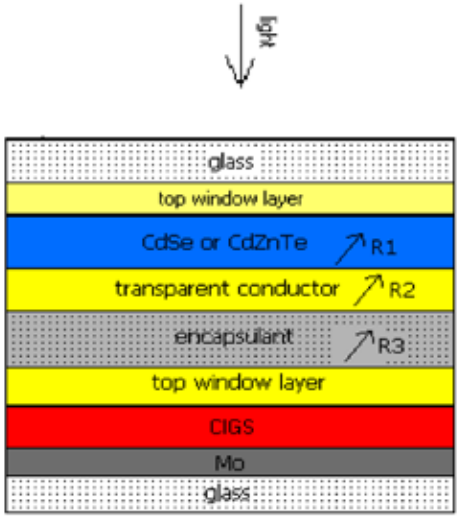
Tandem Solar Cells: $CuInSe_2$-based

- For a monolithically interconnected tandem cell the bottom cell must be sufficiently durable that its performance is not adversely affected by the processing requirements of the top cell
- Any successful tandem device fabrication process will require a more durable bottom cell or a more benign deposition for the top cell
- Tandem cells have recently been fabricated at IEC



Tandem Solar Cells: II-VI-based Top Cells

- USF has proposed a 4-terminal tandem device as an effective means of achieving high efficiency with thin film compound semiconductor based absorbers
- The bottom cell is assumed to be CIGS with efficiencies of 16-19%
- CdSe and $Cd_{1-X}Zn_XTe$ (CZT) are viable candidates for the top cell since both can have a bandgap of 1.7eV (CZT is tunable)



Polymer Substrates

- Unlike metal foils, which are also lightweight and flexible, polymer substrates are (a) electrically insulating, (b) inert in the $Cu(InGa)Se_2$ deposition environment, and (c) are not a source of impurities diffusing into the growing film
- However, polymers have a limited operating temperature and can poorly affect adhesion between the absorber and back contact
- IEC has modified its in-line evaporation system for deposition onto polyimide film
- Foster-Miller, Inc. is currently engaged in research aimed at developing CIGS thin film solar cell devices supported by PBO film

Mo on kapton

Polymer Substrates: Materials Thermal Analysis

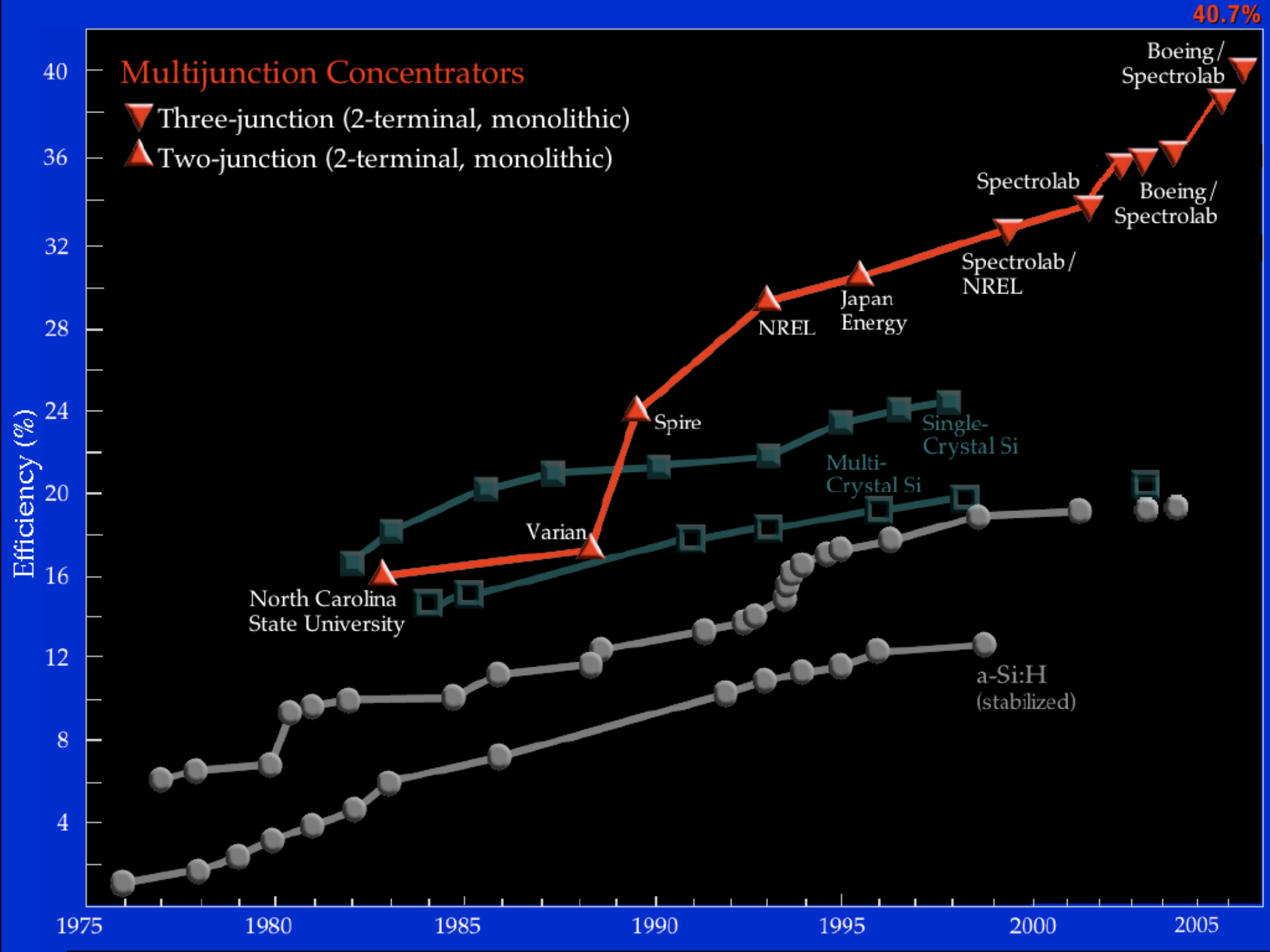
- The NASA/OAI group has performed a thermogravimetric analysis (TGA) of 5 thin film polymer coupons metallized by Techni-Met, Inc

Thin Film Polymer Coupon Data				1st Weight Change to 250°C (Water Loss)		Onset Temp. Decomp. (°C)	2nd Weight Change		Residue (WT % @ °C)	
Polymer Type	Metal Layer	Thickness (mil)	Resistivity (ohm/sq)	Max. Rate WT Loss (°C)	WT Loss %		Max. Rate WT Loss (°C)	WT Loss %	WT %	T (°C)
1. Upilex	Mo	1	0.6	119.7	1.9	534.5	614.3	32.4	65.7	900
2. Upilex	Mo	1	1.0	108.3	1.6	523.2	611.3	34.4	63.9	900
3. Upilex	Mo	1	7.5	122.4	1.8	525.4	610.8	35.9	62.1	900
4. Upilex	Pd	1	< 5.0	114.6	2.1	530.1	612.8	33.5	64.4	850
5. PET	Au	10	2.2	169.7	1.4	360.6	427.4	87.2	11.4	650

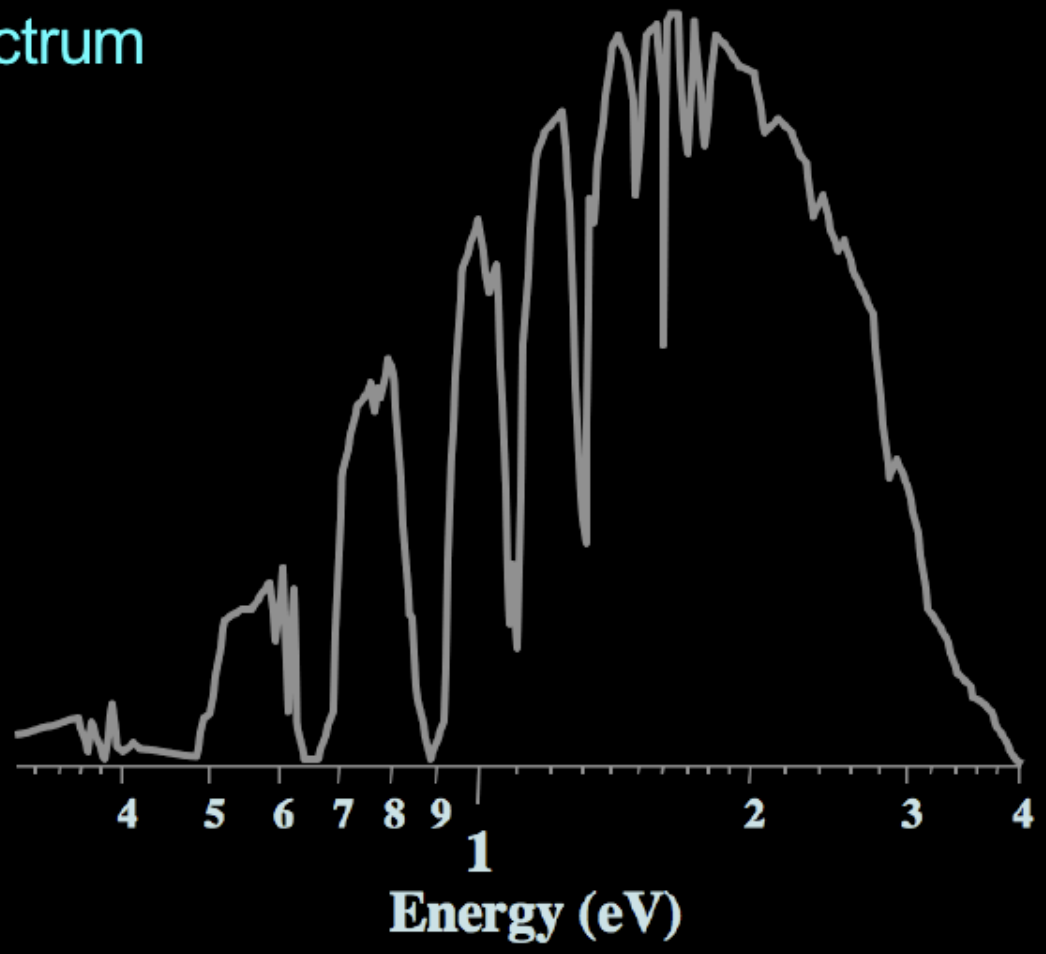
Polymer Substrates: Roll-to-Roll Performance

- Device uniformity for $Cu(InGa)Se_2$ films on upilex in a single run over a 5' length of web are shown below
- The average V_{OC} was 0.529 V and average efficiency was 10%
- The $Cu(InGa)Se_2$ composition and thickness data indicate acceptable uniformity in film properties over the web surface for a given deposition

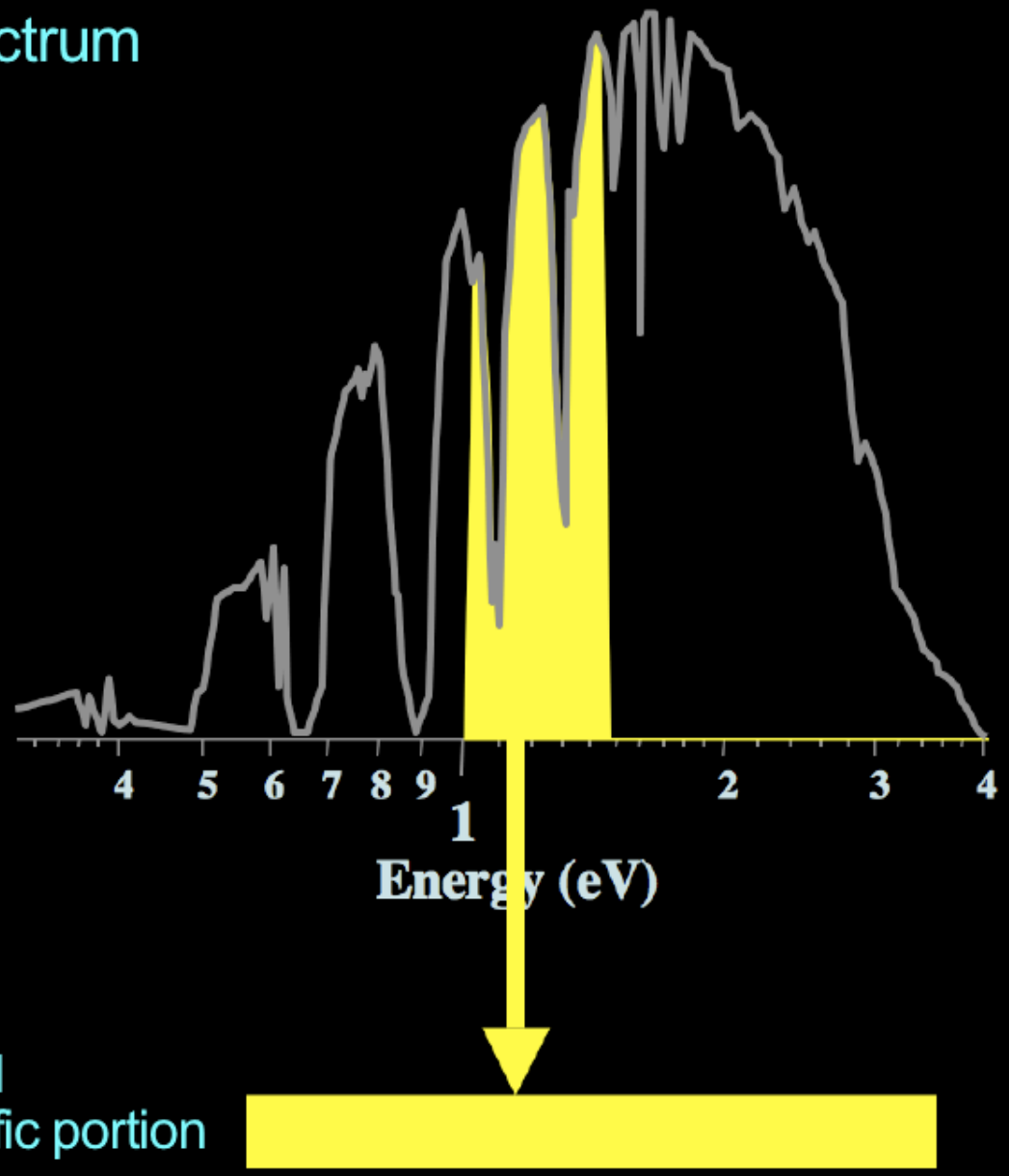
Position (inch)	Cell #	Voc (V)	Jsc (mA/cm2)	FF (%)	Eff (%)
20	3	0.517	29.6	56.7	8.7
	4	0.533	30.2	63.0	10.2
30	1	0.527	30.6	60.1	9.7
	2	0.521	31.0	60.1	9.7
	3	0.534	30.2	62.4	10.1
	4	0.532	30.3	60.8	9.8
40	1	0.529	30.7	62.5	10.1
	2	0.528	30.6	62.6	10.1
	3	0.532	30.9	62.6	10.3
	4	0.528	30.8	62.7	10.2
50	1	0.528	31.0	60.5	9.9
	2	0.533	30.9	62.2	10.2
	3	0.529	30.4	60.1	9.7
	4	0.533	30.8	63.0	10.4
60	1	0.529	30.4	61.1	9.8
	2	0.526	31.0	61.6	10.1
	3	0.535	30.4	61.6	10.0
	4	0.531	31.0	62.4	10.3
	Best	*0.533*	*30.8*	*63.0*	*10.4*
	Avg	*0.529*	*30.6*	*61.4*	*10.0*
	Stdev (%)	*0.86*	*1.2*	*2.6*	*3.9*


40.7%
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
Varian
North Carolina State University
a-Si:H (stabilized)

Terrestrial Solar Spectrum

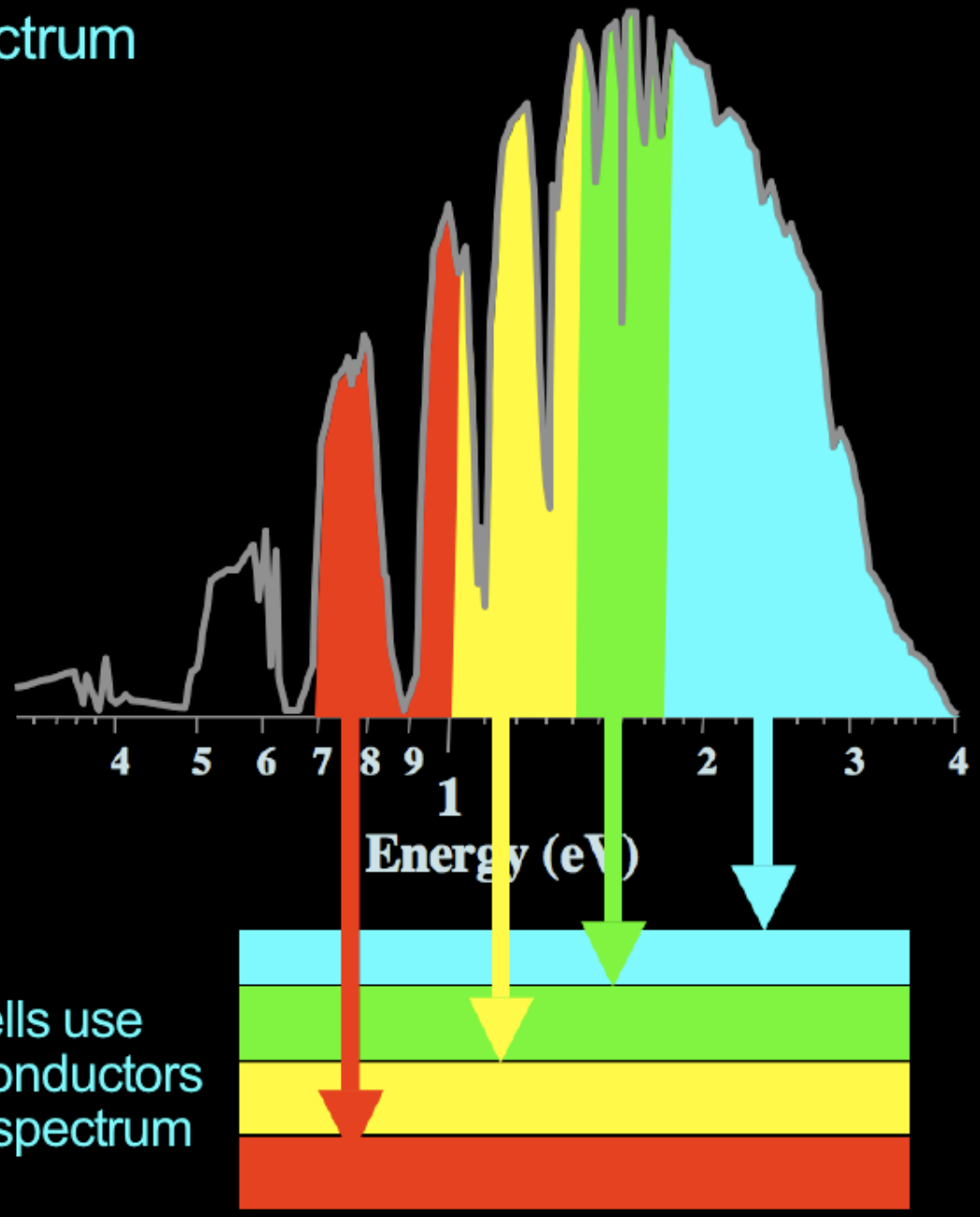


Terrestrial Solar Spectrum



Conventional solar cell responds to one specific portion of the solar spectrum

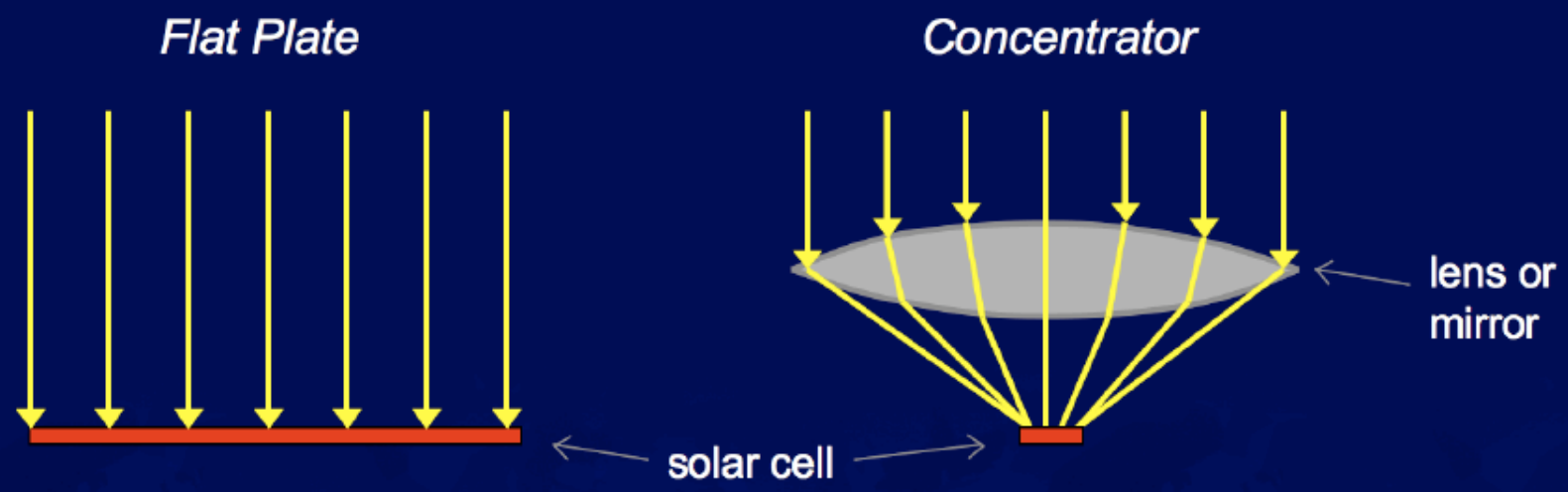
Terrestrial Solar Spectrum



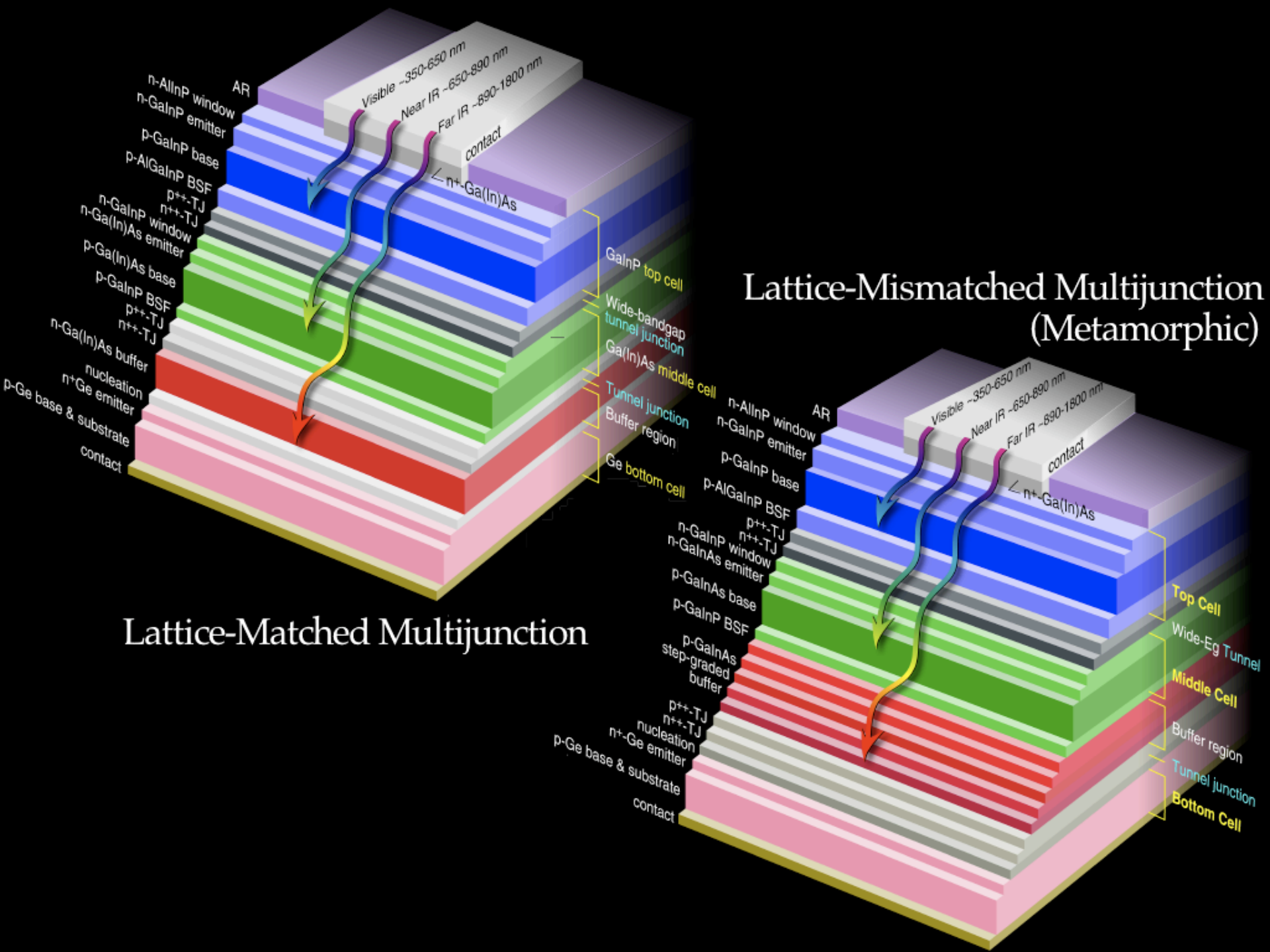
Multiple-junction solar cells use stacks of different semiconductors to use more of the solar spectrum

Concentrator Photovoltaics

Use optics to reduce the cell area *(from 2 to more than 1000 times)*



Shifts the major system cost from the cell to the optics
Can afford more efficient, expensive cells


Lattice-Matched Multijunction
AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-Ga(In)As emitter
p-Ga(In)As base
p-GaInP BSF
p++-TJ
n++-TJ
n-Ga(In)As buffer
nucleation
n+Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
GaInP top cell
Wide-bandgap tunnel junction
Ga(In)As middle cell
Tunnel junction
Buffer region
Ge bottom cell
Lattice-Mismatched Multijunction (Metamorphic)
AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-GaInAs emitter
p-GaInAs base
p-GaInP BSF
p-GaInAs step-graded buffer
p++-TJ
n++-TJ
nucleation
n+-Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
Top Cell
Wide-Eg Tunnel
Middle Cell
Buffer region
Tunnel junction
Bottom Cell

Spectrolab **GaInP/GaInAs/Ge Cell**

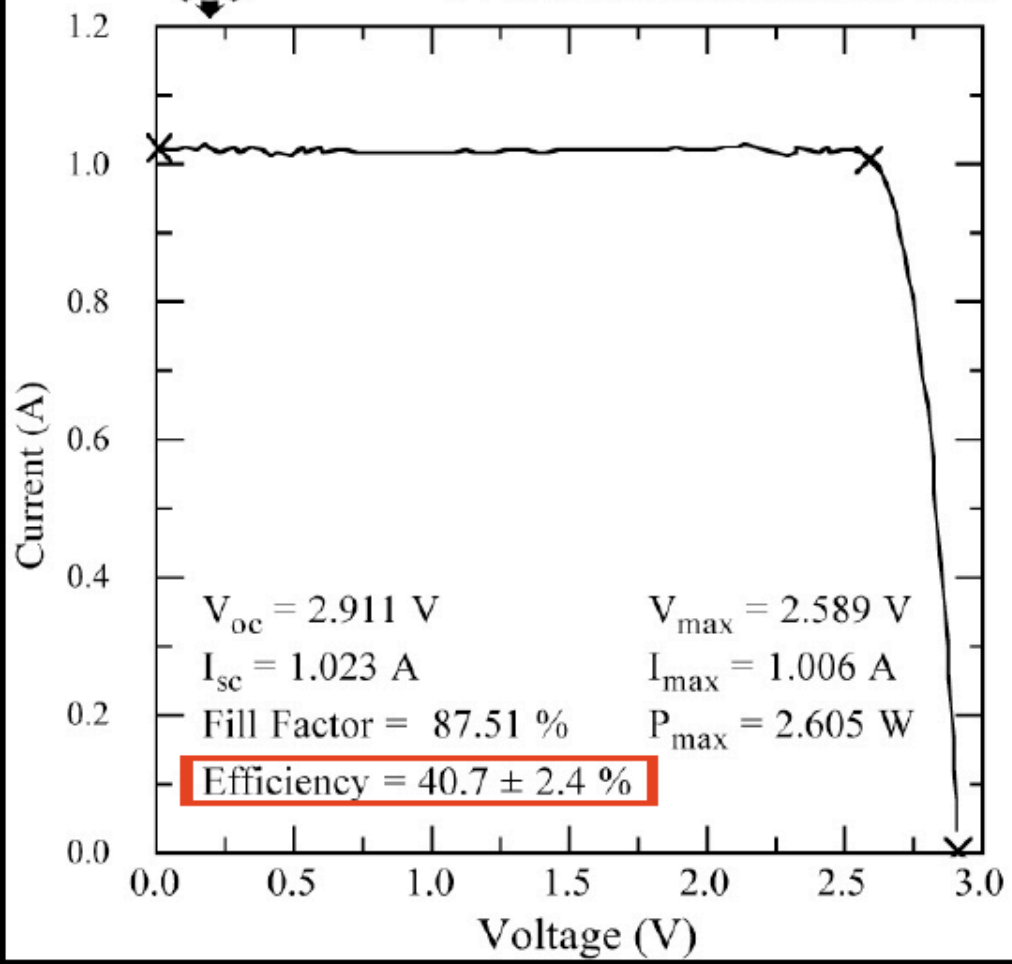
Sample: 6997-C407 Device Temperature = 25.0°C

Wed, Sep 6, 2006 7:46 PM area used = 0.26685 cm^2

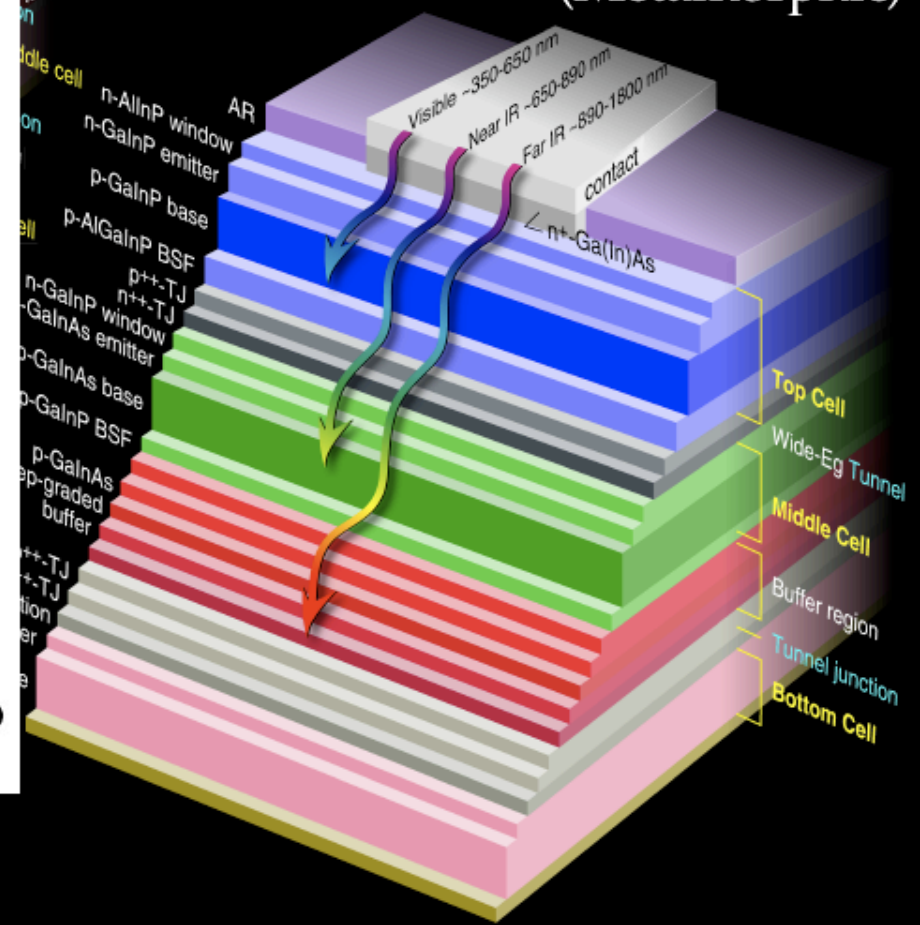
HiPer Direct Reference Irradiance: 240037.1 W/m^2

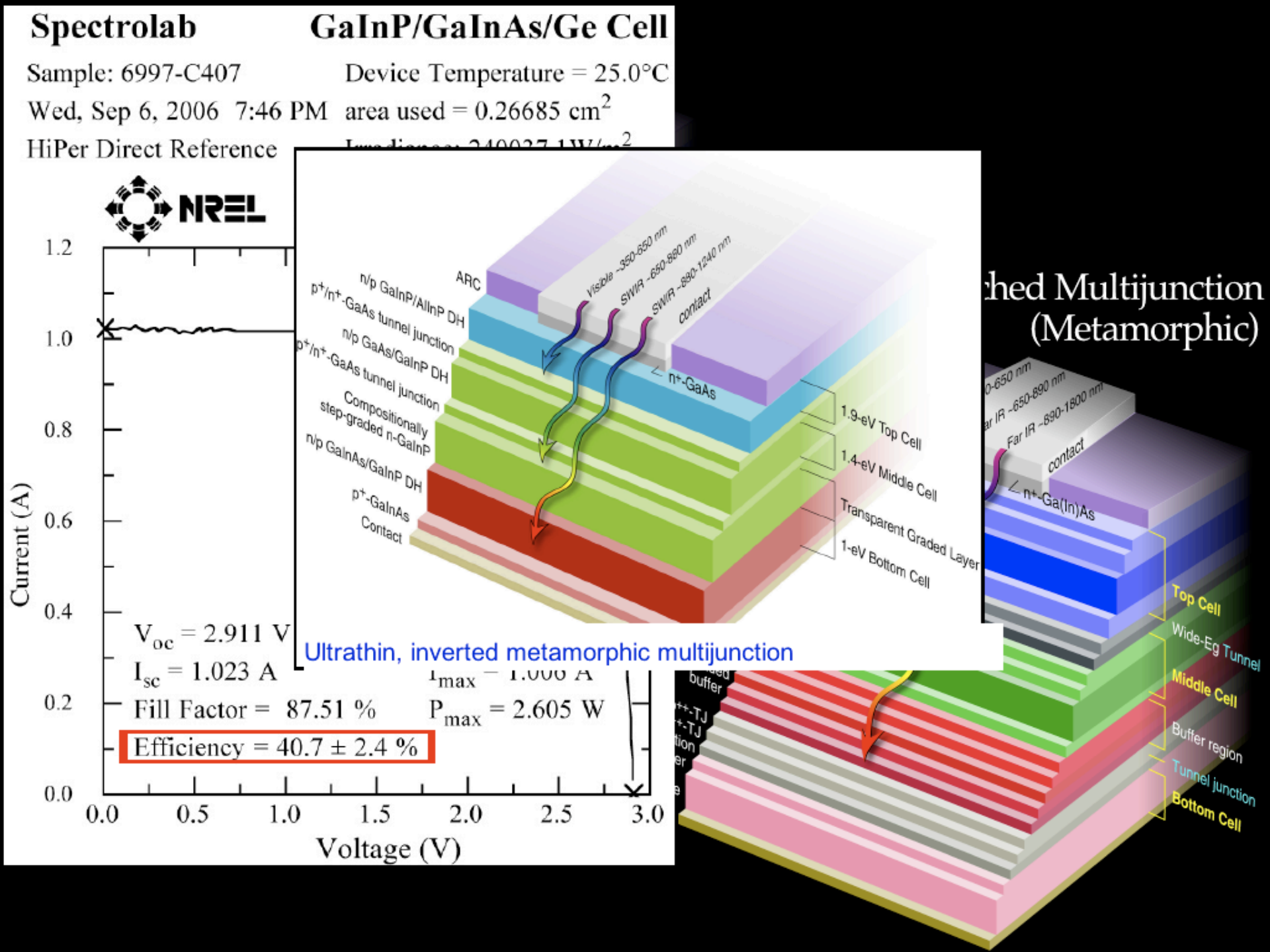
NREL HIPSS

PV Performance Characterization Team



Lattice-Mismatched Multijunction (Metamorphic)




Spectrolab
GaInP/GaInAs/Ge Cell
Sample: 6997-C407
Device Temperature = 25.0°C
Wed, Sep 6, 2006 7:46 PM
area used = 0.26685 cm2
HiPer Direct Reference
NREL
Current (A)
Voltage (V)
Voc = 2.911 V
Isc = 1.023 A
Fill Factor = 87.51 %
Pmax = 2.605 W
Efficiency = 40.7 ± 2.4 %
ARC
n/p GaInP/AlInP DH
p+/n+-GaAs tunnel junction
n/p GaAs/GaInP DH
p+/n+-GaAs tunnel junction
Compositionally step-graded n-GaInP
n/p GaInAs/GaInP DH
p+-GaInAs Contact
Visible ~350-650 nm
SWIR ~650-880 nm
SWIR ~880-1240 nm
contact
n+-GaAs
1.9-eV Top Cell
1.4-eV Middle Cell
Transparent Graded Layer
1-eV Bottom Cell
Ultrathin, inverted metamorphic multijunction
hed Multijunction
(Metamorphic)
Far IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
Top Cell
Wide-Eg Tunnel
Middle Cell
Buffer region
Tunnel junction
Bottom Cell

CPV Companies (USA)

Triple-Junction High Efficiency
(cells/modules/systems)

Spectrolab - CA
Emcore - NM
MicroLink Devices - IL
Opel International - CT

Modules/Systems

Amonix - CA
JX Crystals - WA
SolFocus - CA
Practical Instruments - CA
Stellaris - MA
Soliant - CA
Energy Innovations - CA
Midway Labs - IL
Prism Solar Technologies - NY
Enfocus Engineering - CA
Solaria - CA
Cool Earth Solar - CA
Greenvolts Inc. - CA

CPV Systems

www.amonix.com

Solar Systems
(reflective)

www.solarsystems.com.au

Amonix
(refractive)

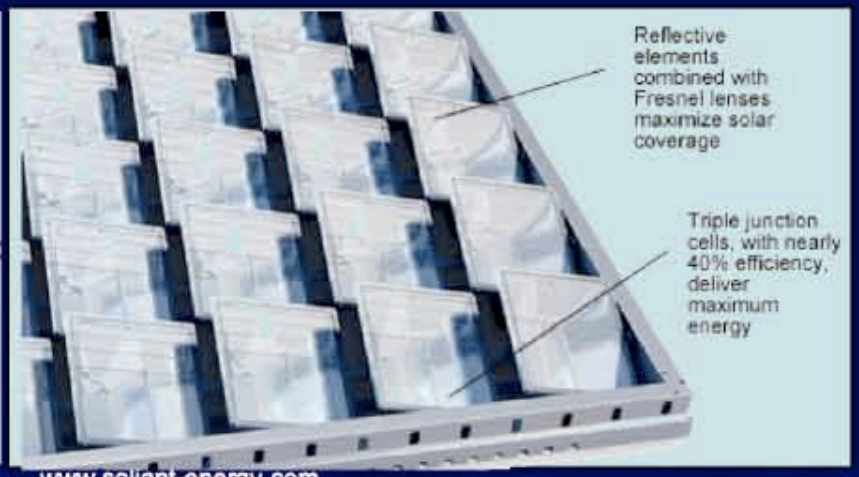
www.Solfocus.com

Solfocus
(reflective & optical rod)

Low-Profile CPV Systems

www.energyinnovations.com

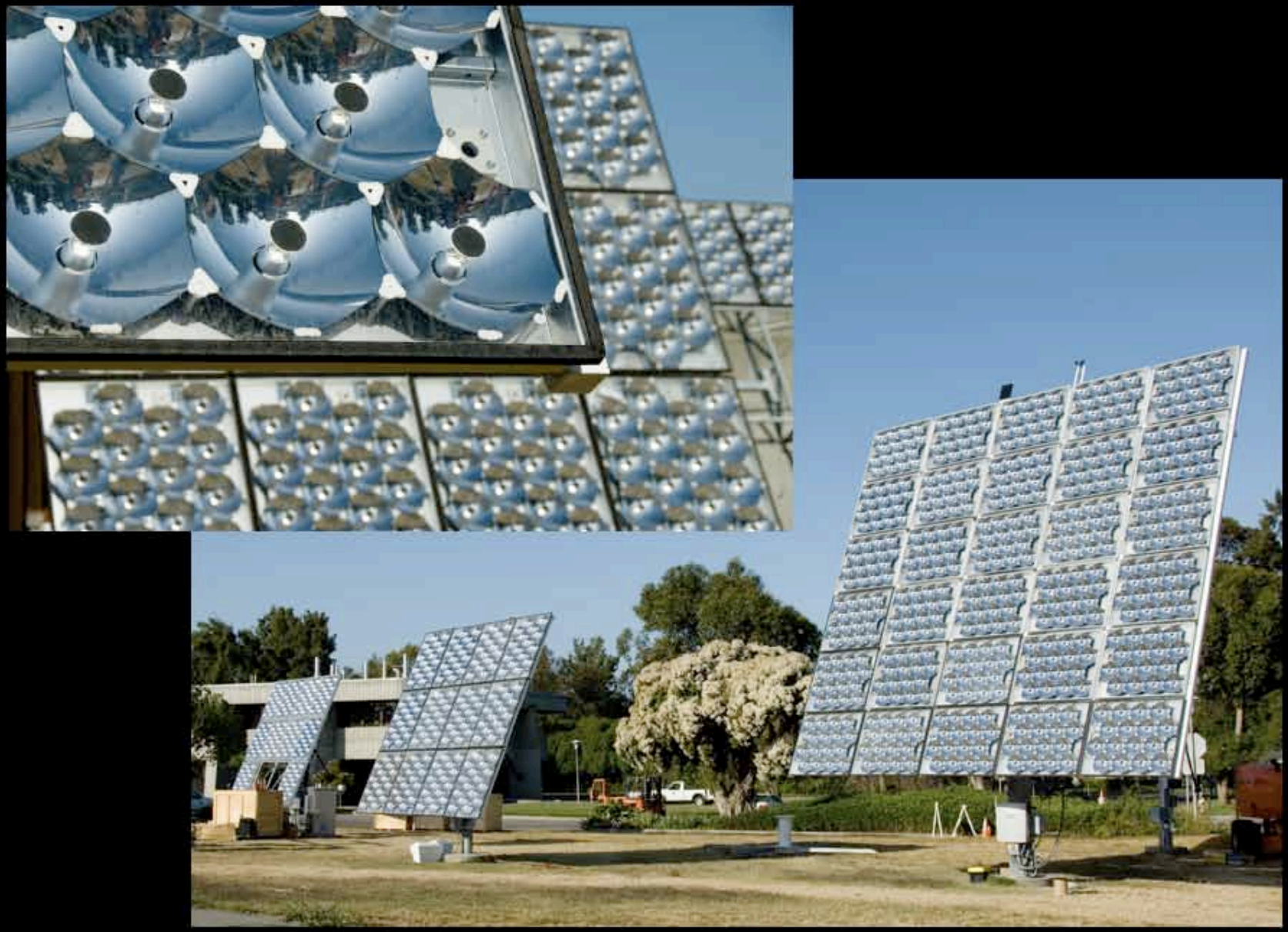
Energy Innovations *(800-suns)*



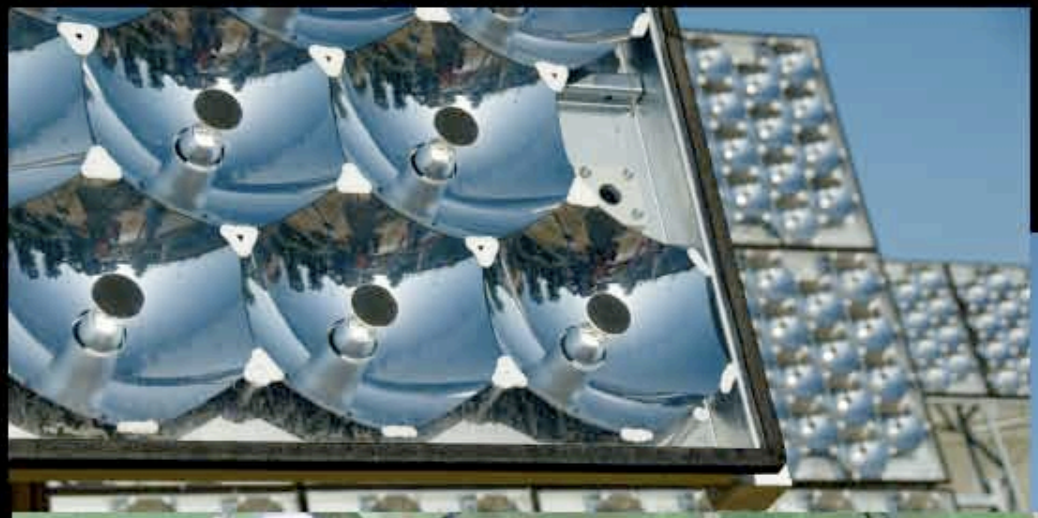
www.soliant-energy.com

Soliant Energy *(500-suns)*

Commercial rooftops and utility targeted



SolFocus (www.SolFocus.com)



SolFocus (www.SolFocus.com)

SolFocus (www.SolFocus.com)

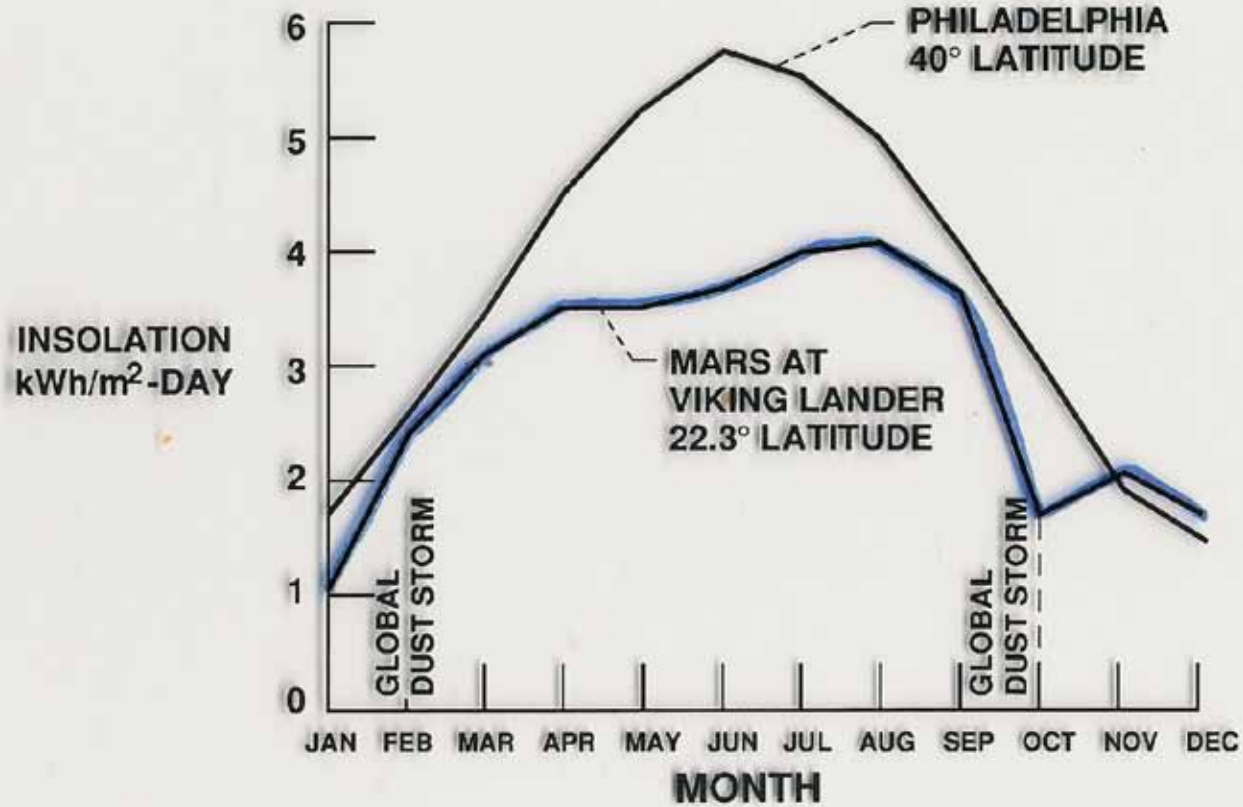
Pathfinder and Sojourner Rover: **a solar-powered mission to Mars** July 1996

The Sojourner rover was about the size of a microwave oven!

Geoff Landis poses with the Sojourner rover

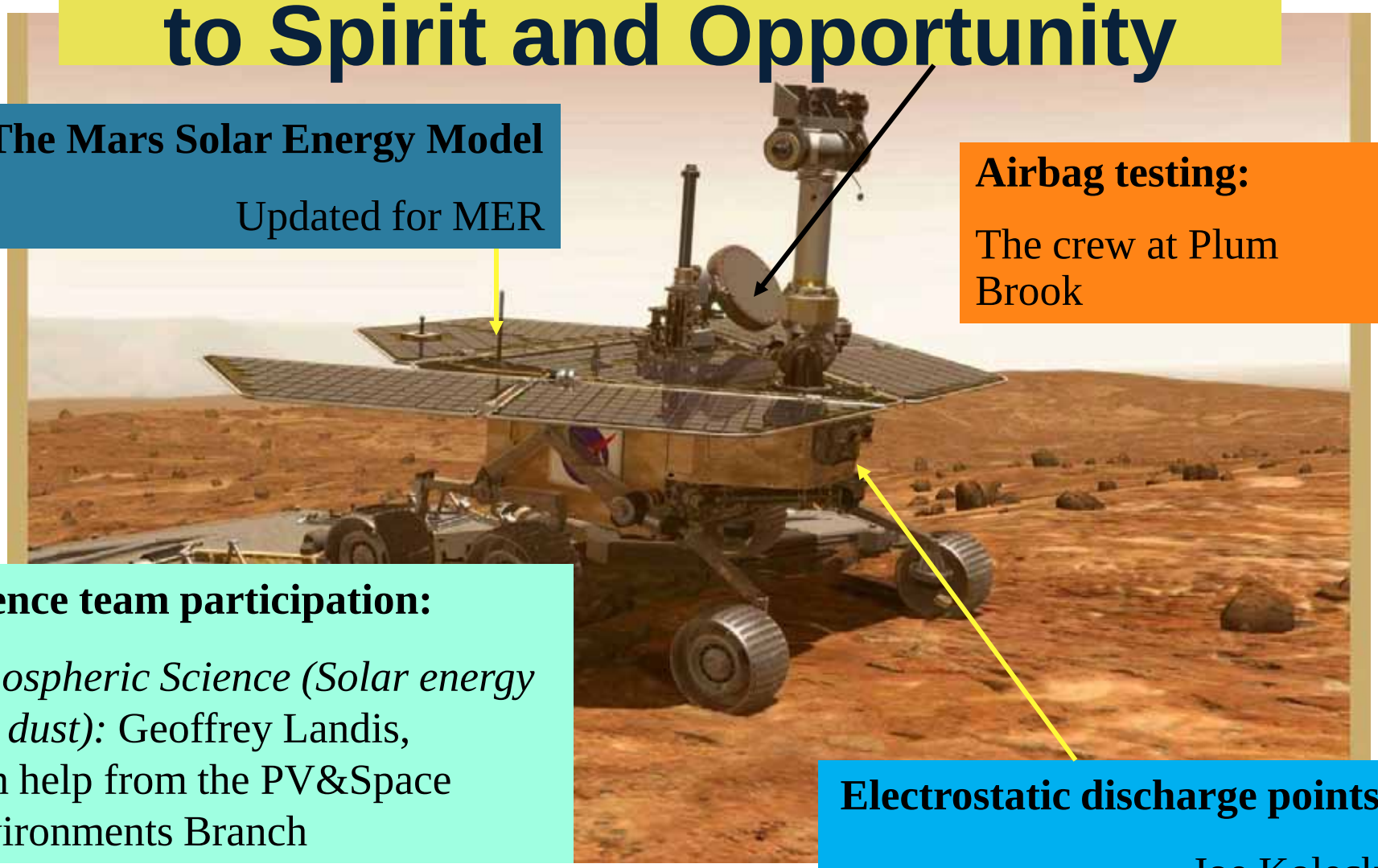
SOLAR INSOLATION ON MARS AND IN PHILADELPHIA IN kWh/m^2-DAY

MARS INSOLATION SHIFTED BY 3 MONTHS RELATIVE TO PHILADELPHIA



CD-90-4713

NASA Glenn Contributions to Spirit and Opportunity



The Mars Solar Energy Model

Updated for MER

Airbag testing:

The crew at Plum Brook

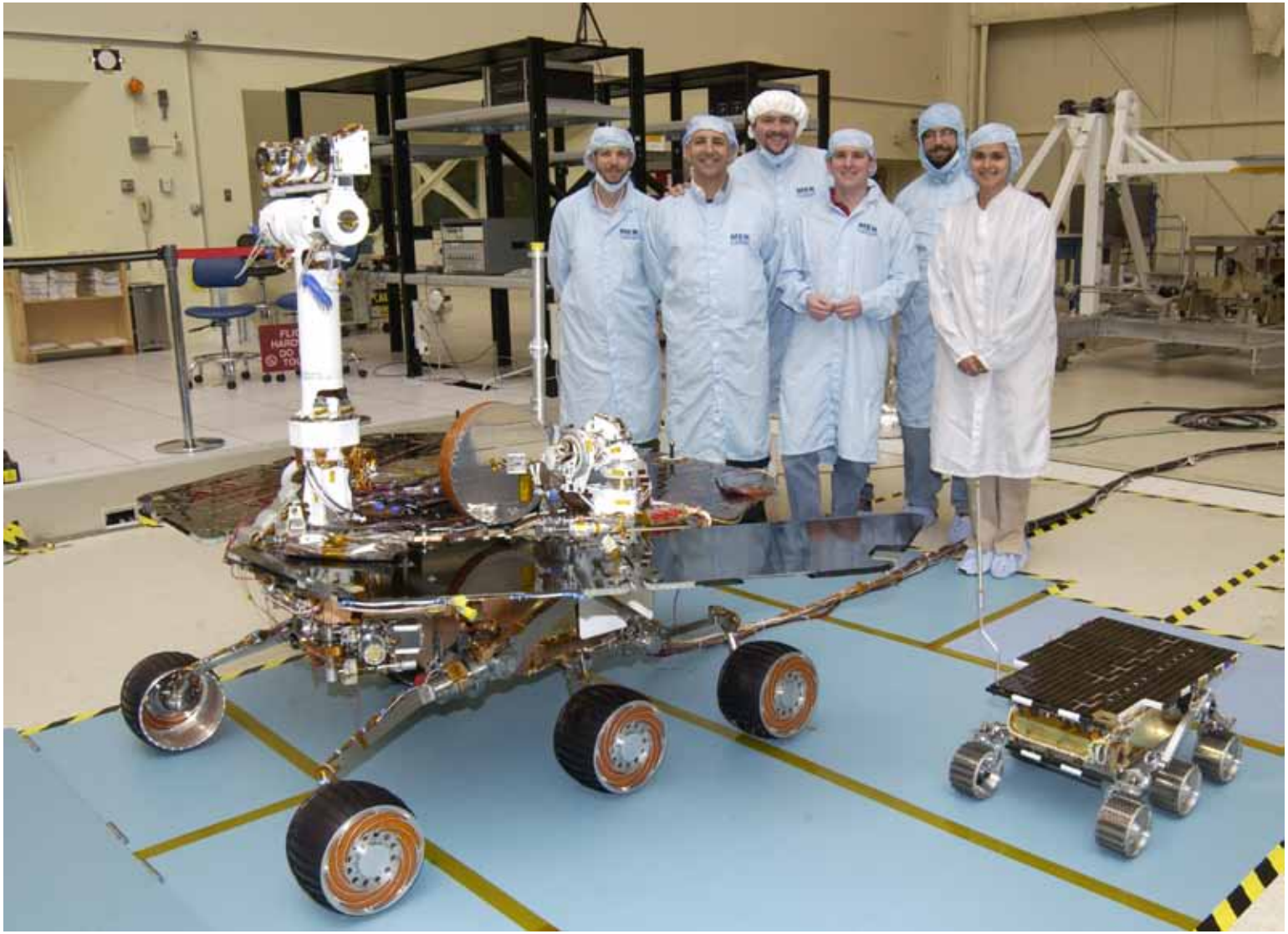
Science team participation:

Atmospheric Science (Solar energy and dust): Geoffrey Landis, with help from the PV&Space Environments Branch

Electrostatic discharge points:

Joe Kolecki

The Mars Exploration Rover compared to Sojourner



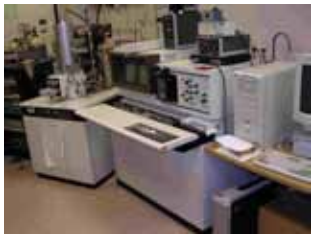
SEMICONDUCTOR DEVELOPMENT FACILITIES AT GRC

III-V Organo Metallic Vapor Phase Epitaxy

Multiple in-house OMVPE systems and a NEW SOA ($1.75M) OMVPE SYSTEM INSTALLED and Running 8/05

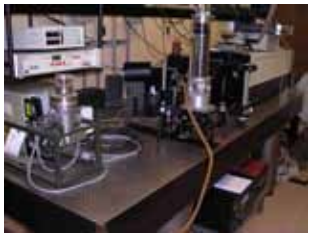
Semiconductor Materials Characterization

XRD



FE-SEM

PL



ECV, Hall

Semiconductor Device Fabrication

E-beam, resistive, and magnetron sputtering evaporation

Photolithography with IR backside alignment

Device Characterization

Triple source solar simulator

Filter and monochromator QE

Measurement Tools

Lambda 950

Dektak IIA

HL5500PC Hall System

X'pert PRO PW3040

S-3000 with EDAX

Plasma Interactions Facility

The Plasma Interactions Facility at NASA GRC is the only full time national facility that can do LEO plasma interactions, GEO spacecraft charging, and Paschen discharge research in the same facility. The facility features 3500 square feet of laboratory space dedicated to simulating the space plasma environment. The laboratory houses four unique research test installations:

(1) Low Earth Orbit Plasma Interactions Test Chamber (Vertical Chamber)

(2) Geosynchronous Charging Simulator Test Chamber (Teney Chamber)

(3) Bemco Vacuum Test Chamber

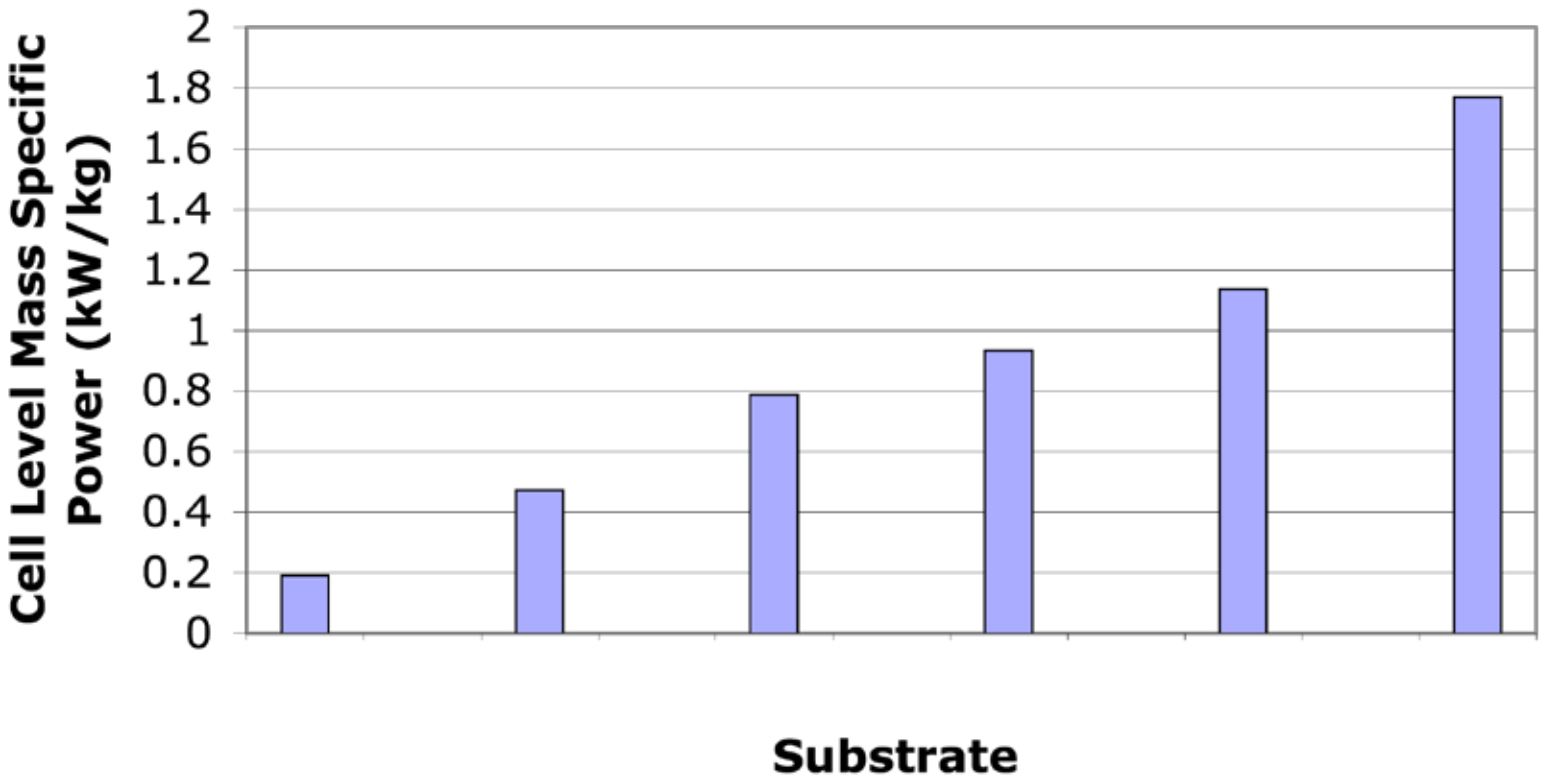
(4) Small Bell Jar Vacuum test Chamber

NANOCHARACTERIZATION FACILITY

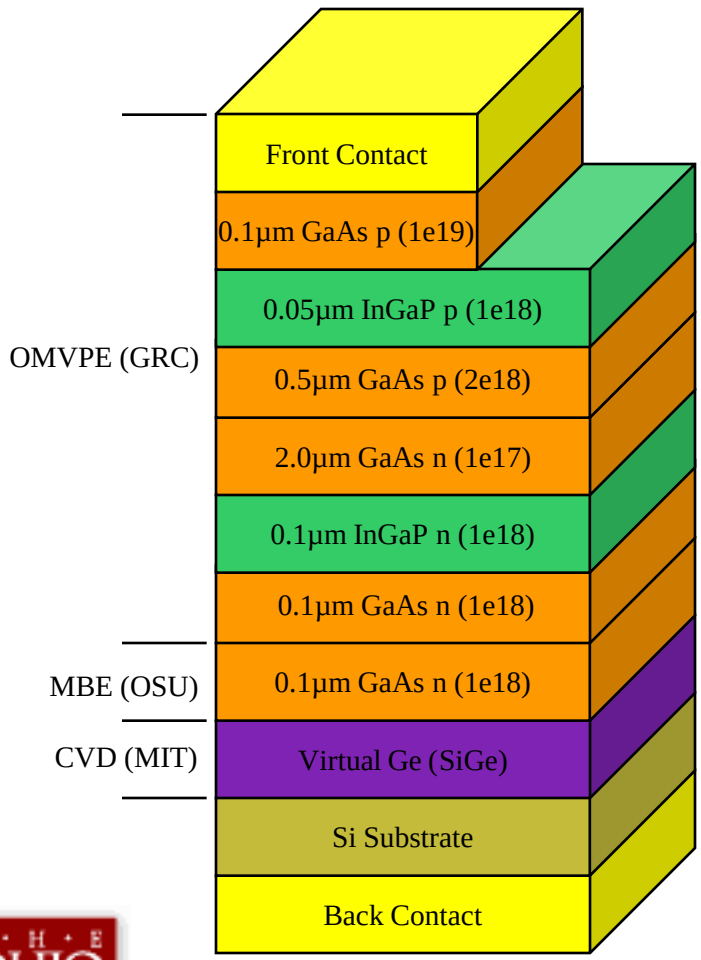
RIT Graduate Student, Dan Byrnes, using STORM
(Scanning Tunneling Optical Resonance Microscopy)

High Efficiency III-V Photovoltaic Development

David M. Wilt, AnnaMaria T. Pal, Jeremiah S. McNatt and Dr. Geoffrey A. Landis
NASA Glenn Research Center
Mark A. Smith, David Scheiman and Phillip P. Jenkins
OAI, Cleveland OH



Gallium Arsenide Solar Cells on Silicon



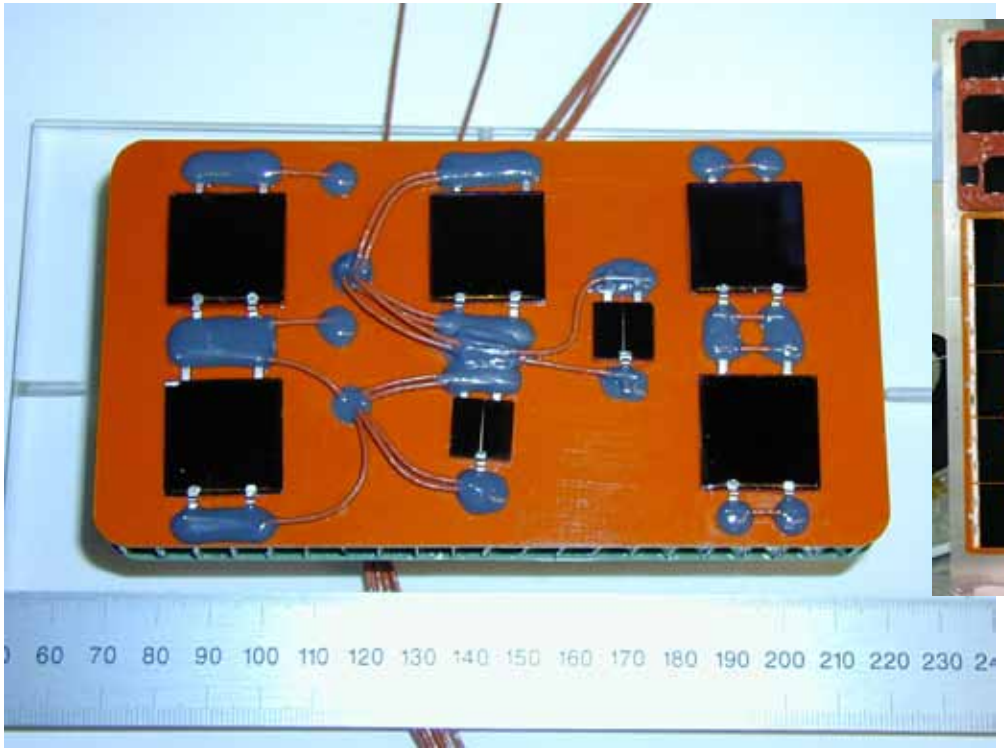
Crystal Growth Reactor at GRC

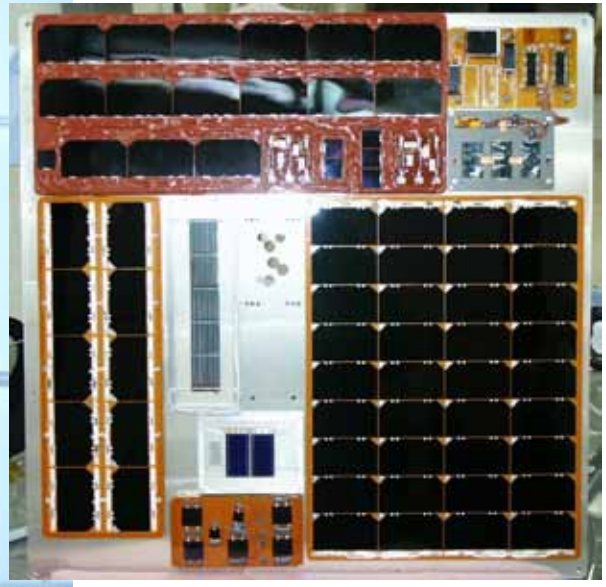
- Step graded SiGe buffer provides low defect density virtual Ge substrate
- p/n GaAs solar cells on these buffers have demonstrated >17%AM0 efficiency and record high V_{oc}.
- Cell area has been increased to 2x2 cm with no loss in performance.

The Ohio State University

Massachusetts Institute of Technology

Gallium Arsenide Solar Cells on Silicon



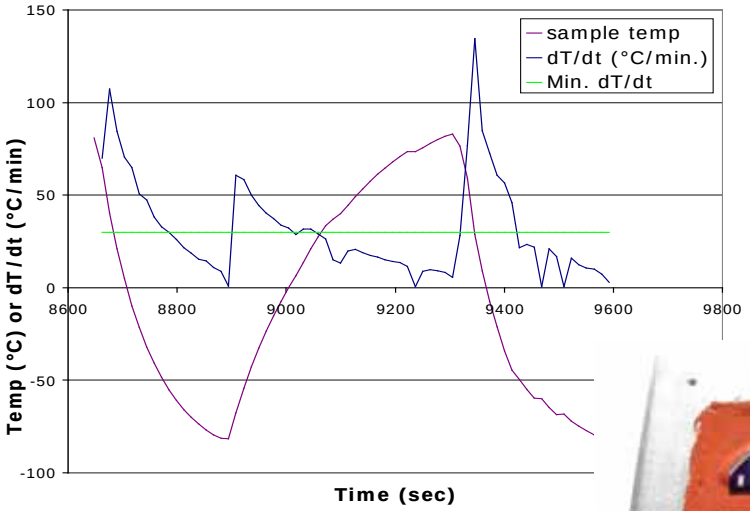


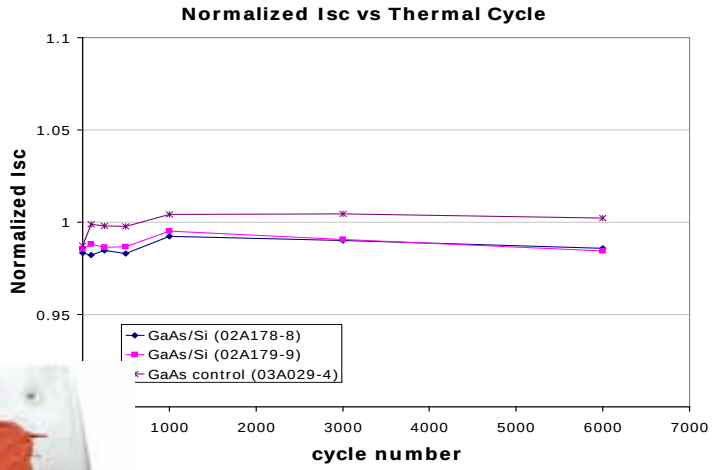
(7) Test Articles in Total:

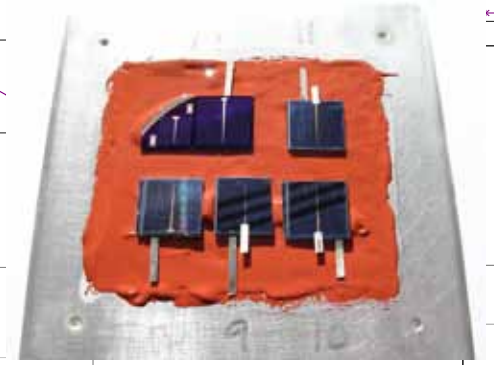
(5) GaAs on Si Cells (3 monitored on-orbit)

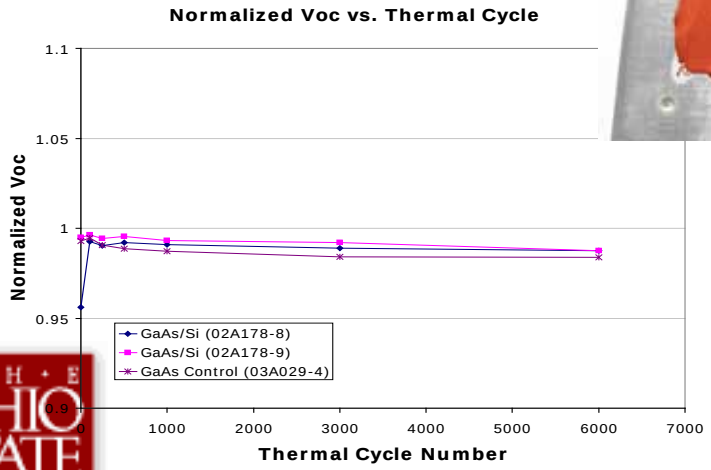
(2) GaAs on GaAs Cells (1 monitored on-orbit)

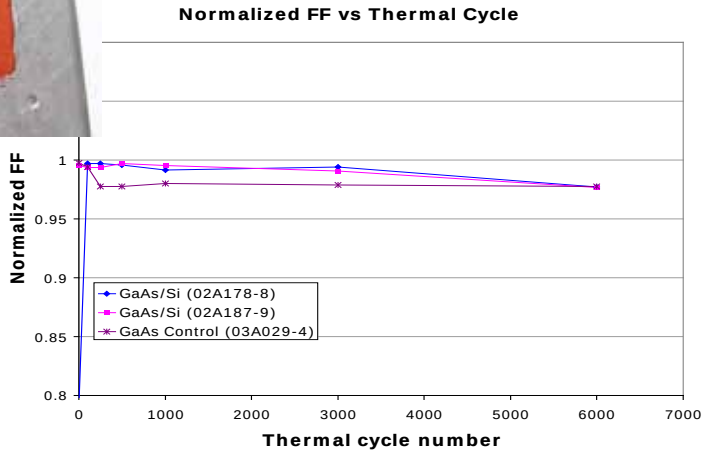
Thermal Cycling of GaAs on Si







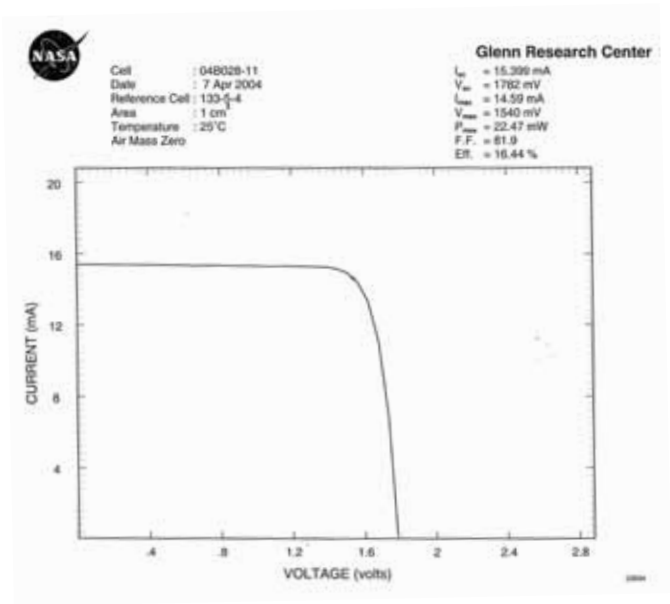


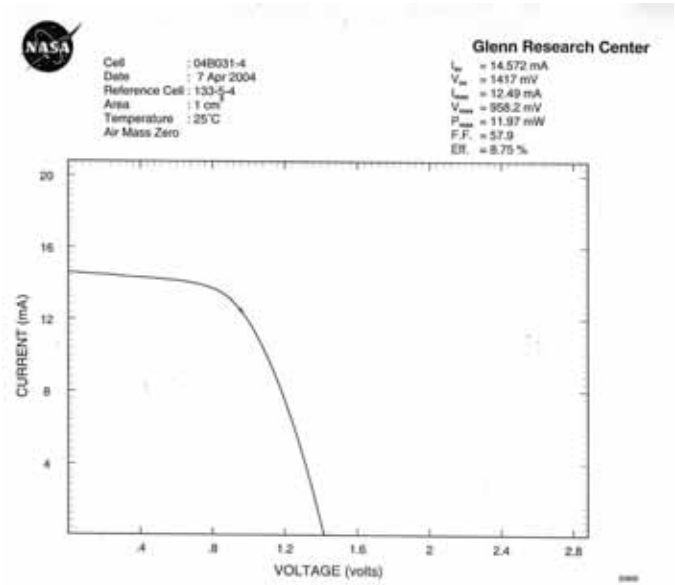


The Ohio State University

Massachusetts Institute of Technology

Tandem III-V Devices on Si
InGaP/InGaAs





On GaAs substrate

Projected Efficiency
with ARC >23%
AM0

On Si substrate

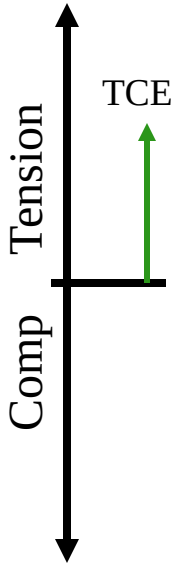
Projected Efficiency
with ARC >12%
AM0 (worlds first)

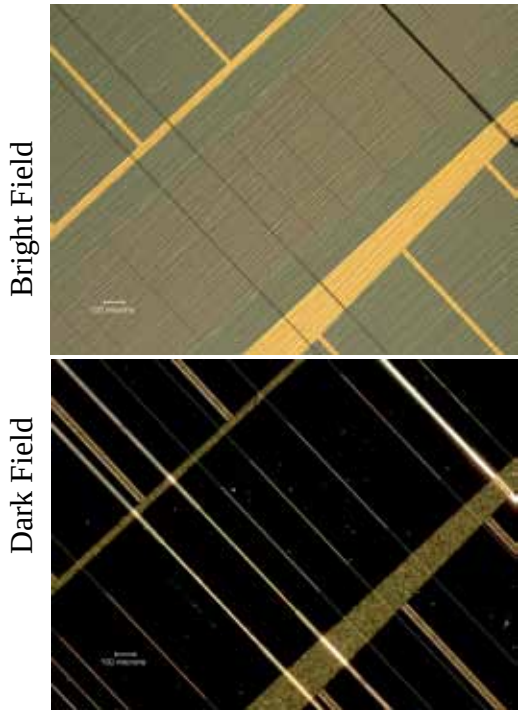
Both Lattice Matched and Lattice Mismatched III-V Tandem Solar Cells Successfully Demonstrated On Silicon

The Ohio State University

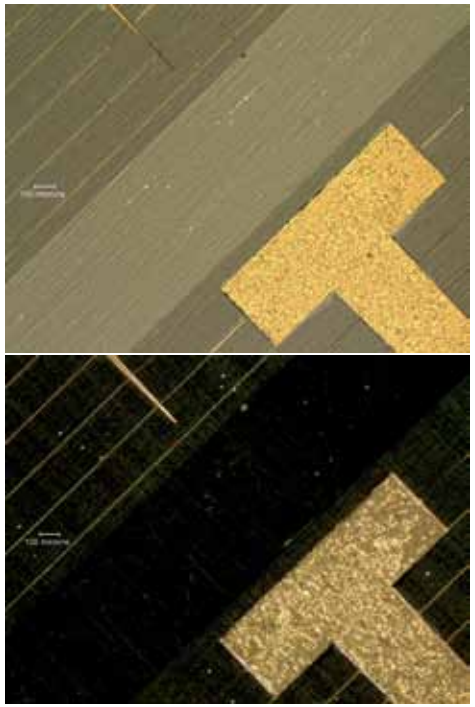
Massachusetts Institute of Technology

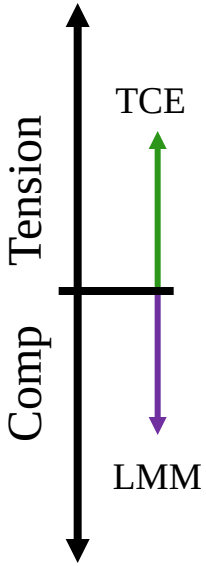
Engineering Away the Cracks





GaAs on Si Cell - showing microcracks induced because of the thermal expansion mismatch





Strain Balanced Cell - microcrack free because the TCE strain is balanced by lattice mismatch strain

Forward Technology Solar Cell Experiment: Environmental Test Results and First On-Orbit Data

Robert Walters, Christopher Garner, Susie Lam, John Vazquez, William Braun, Justin Lorentzen

US Naval Research Laboratory

David Wilt, Mike Krasowski, Larry Greer, and Michael Piszczor

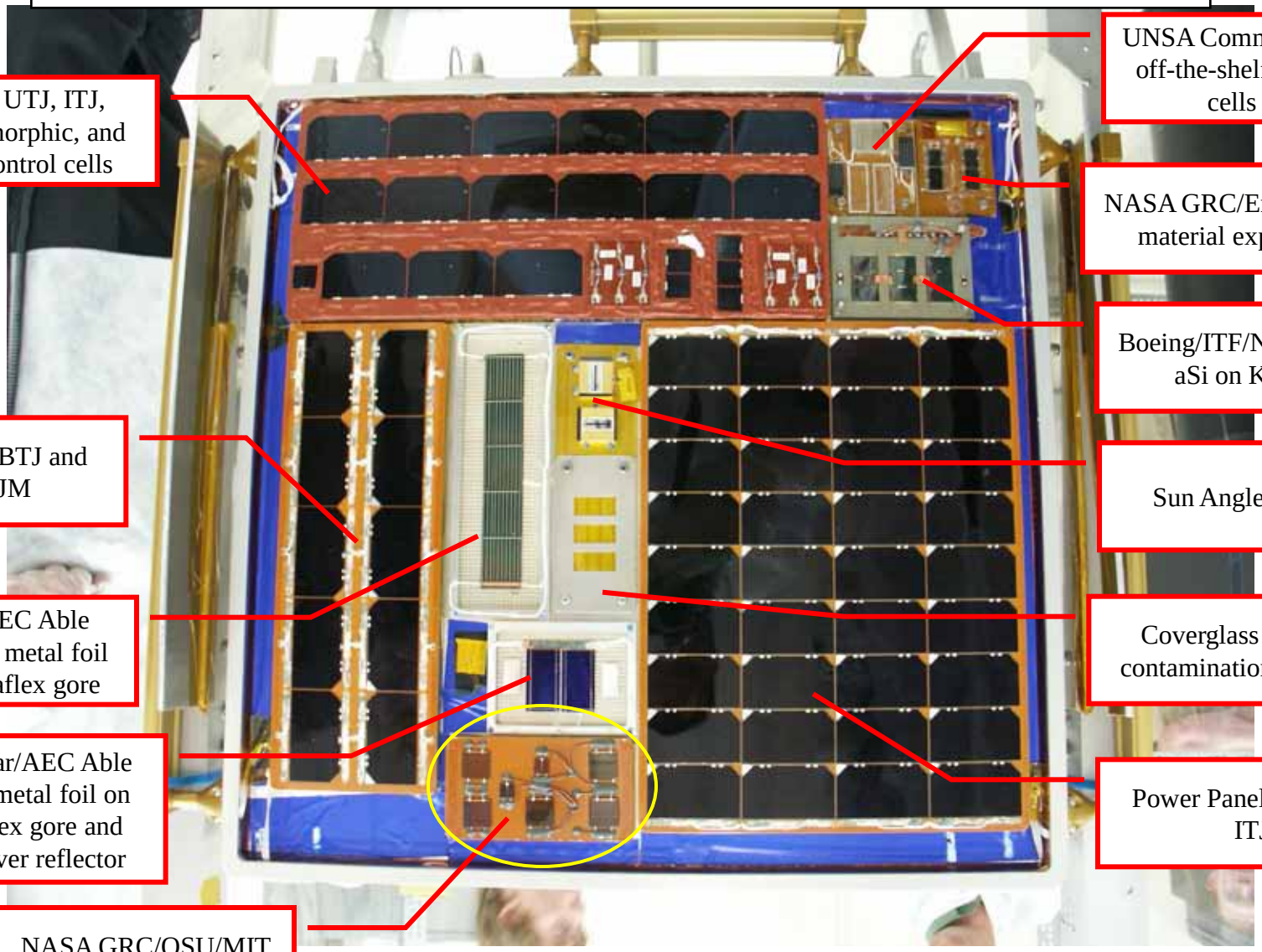
NASA Glenn Research Center

Philip Jenkins – Ohio Aerospace Institute

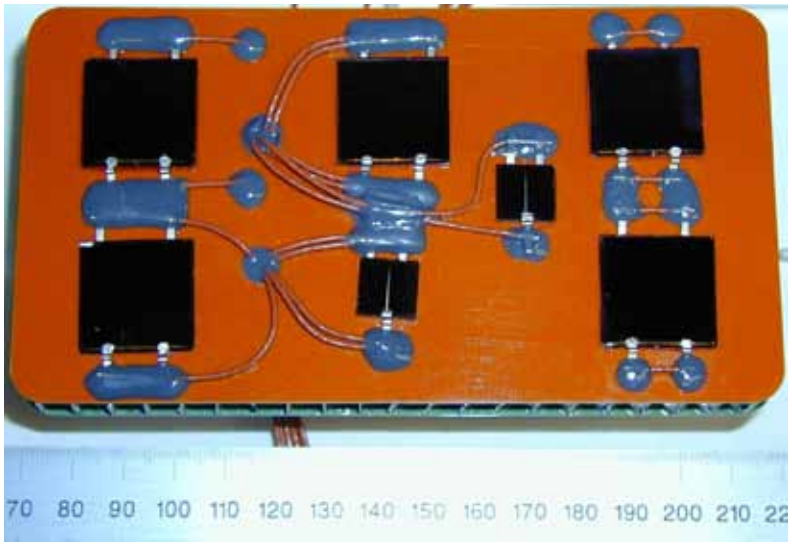
Joe Flatico, QSS

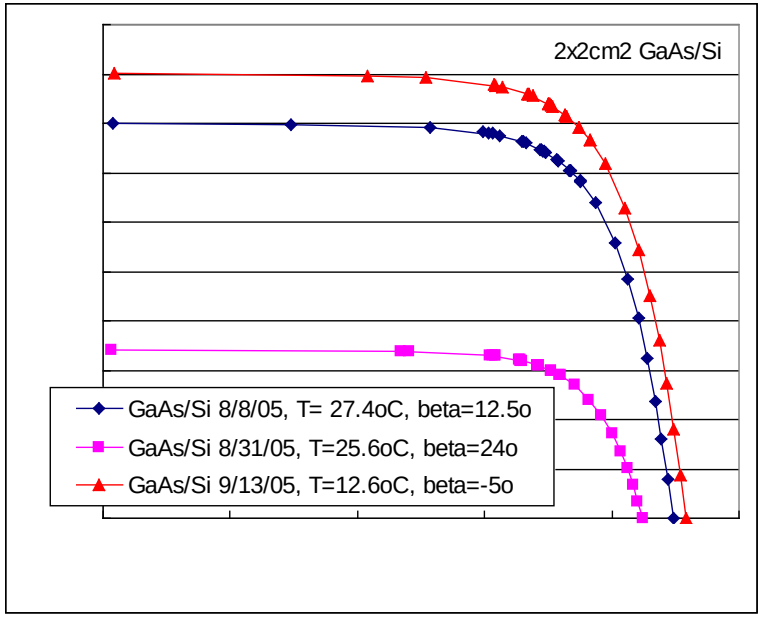
Cdr Robert Bruninga (Ret.) – US Naval Academy

Experiment Deck – Solar Cell Samples



MISSE5 GaAs on Si - GRC/OSU/MIT

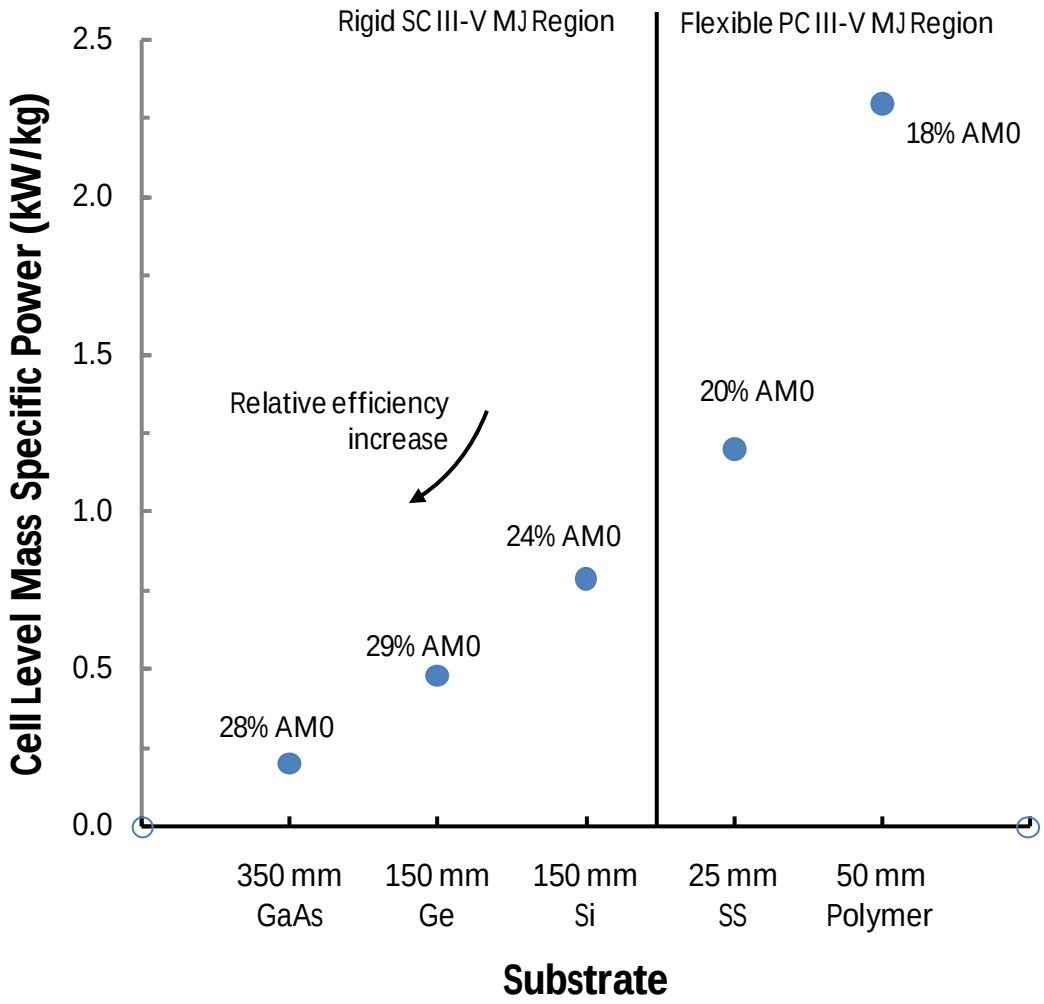


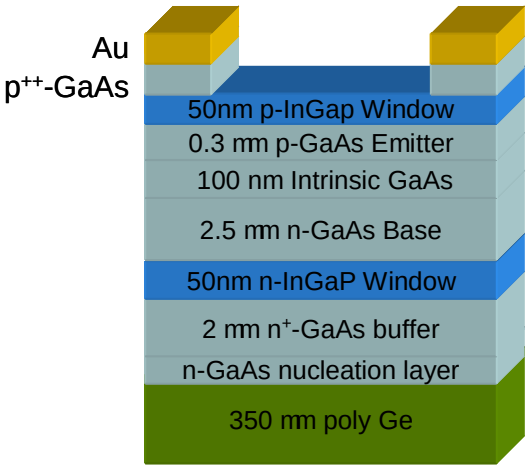


On-Orbit Data – IV Curves

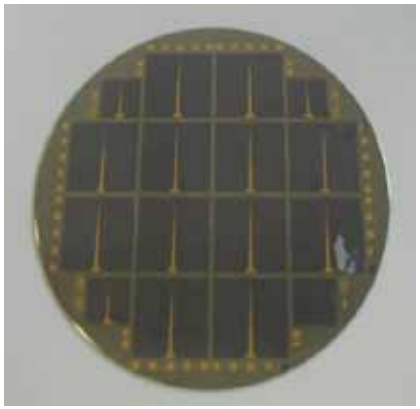
<u>High Efficiency Solar Cells on Silicon Substrates</u>

Record efficiency GaAs on Si devices demonstrated. First demonstration of multi-junction solar cells on Si. Launched to ISS (MISSE5 - NRL) on July 26, 2005

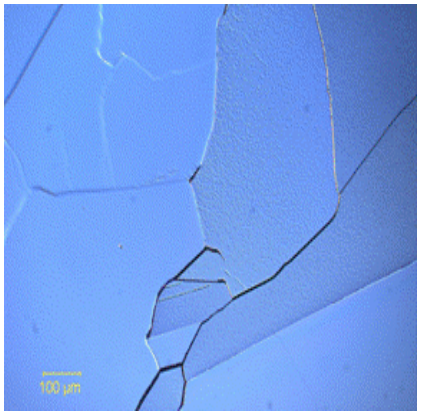

Rigid SC III-V MJ Region
Flexible PC III-V MJ Region
Cell Level Mass Specific Power (kW/kg)
2.5
2.0
1.5
1.0
0.5
0.0
18% AM0
20% AM0
Relative efficiency increase
24% AM0
29% AM0
28% AM0
350 mm GaAs
150 mm Ge
150 mm Si
25 mm SS
50 mm Polymer
Substrate



GaAs *pin* cell

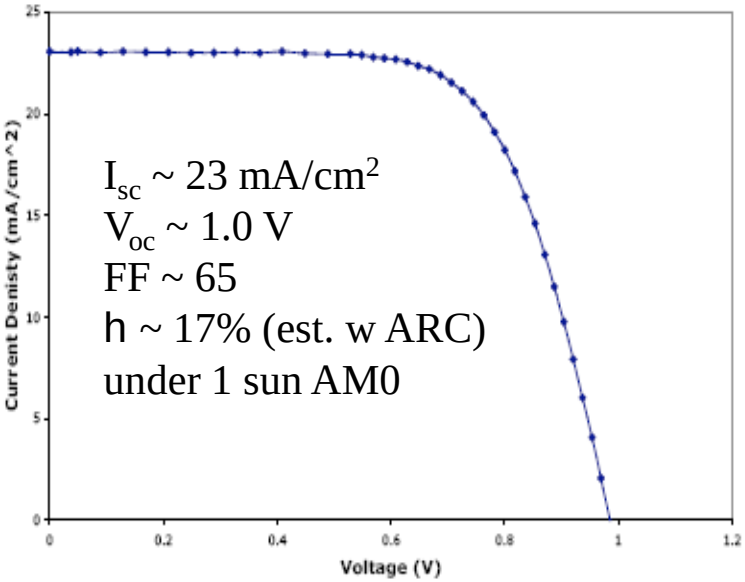


1 cm^2 on poly Ge



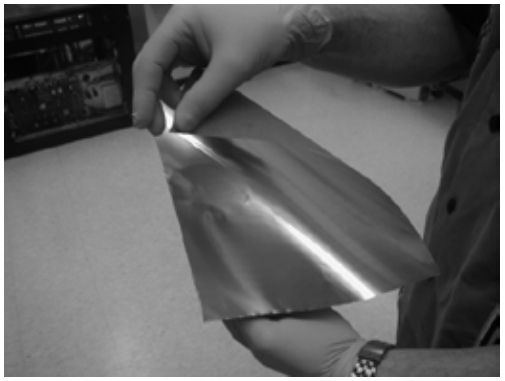
~ 1 mm^2 grains

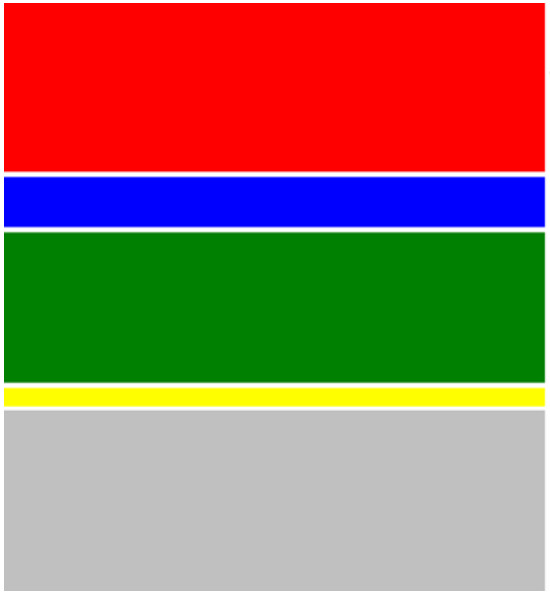
OMVPE



I_{sc} ~ 23 mA/cm^2
V_{oc} ~ 1.0 V
FF ~ 65
h ~ 17% (est. w ARC)
under 1 sun AM0

Material	CTE	Lattice Parameter (nm)
GaAs	5.4	0.565
Ge	6.1	0.566
Mo	6.0	0.315

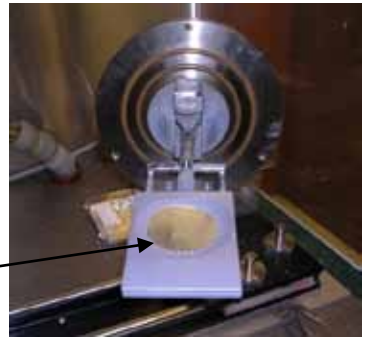




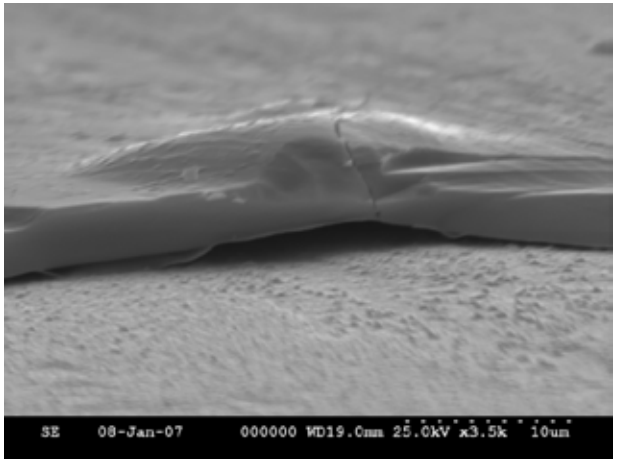
Ge/W/Ti layers deposit by DC sputtering

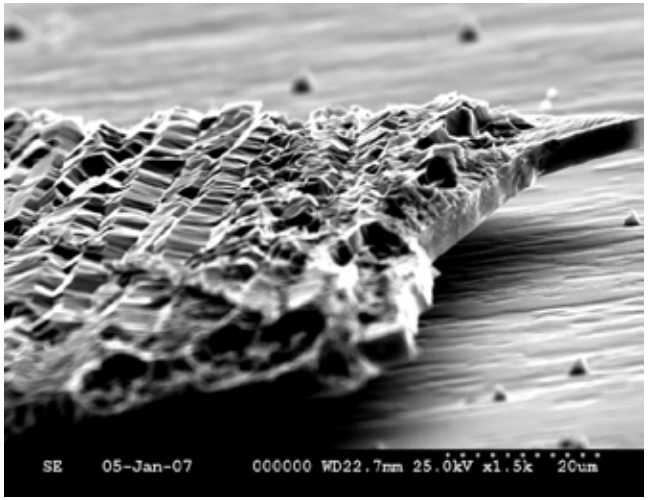
Thermal annealing in Ar or vacuum 600 – 900 ^{o}C

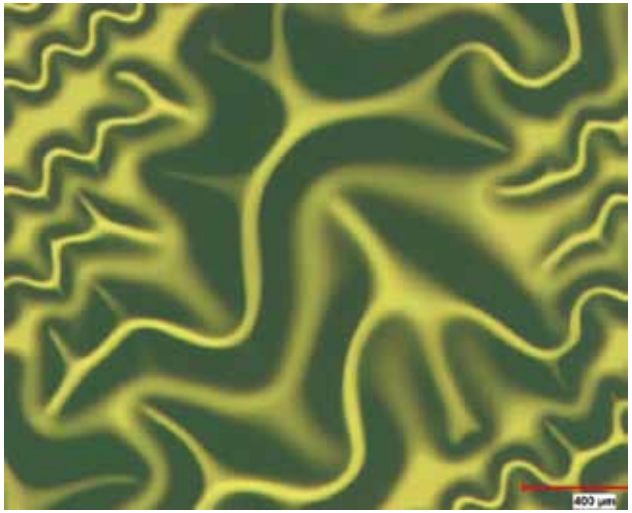
Laser scribed 2” disk
10 mil foil



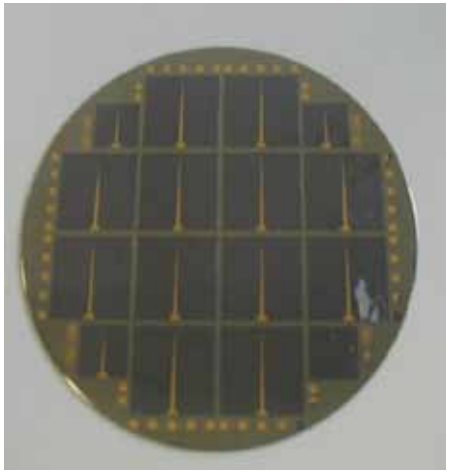
- XRD analysis showed that an Mo_2Ge_3 alloy was forming during annealing
- Literature shows that W/Ge and W/Mo do not form alloys under 1,500 K
- Premium placed on both polishing (< 50 nm RMS) and decontamination
- Lowered the deposition rates (i.e., 0.5 to 0.27 mm/hr) and doubled the W barrier thickness (0.5 to 1.0 mm)



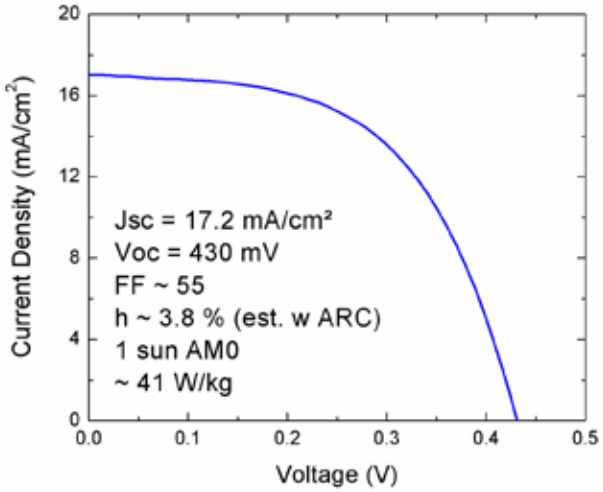


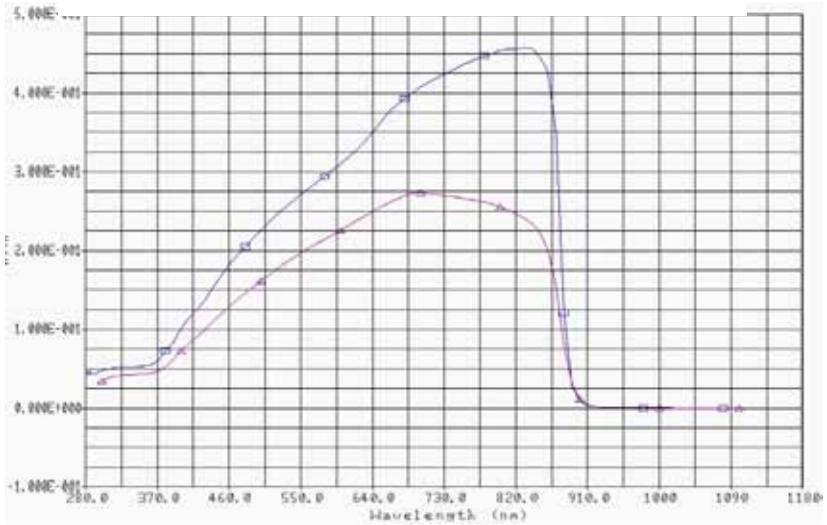


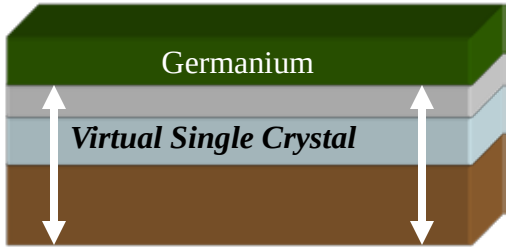
Recrystallized Ge (~10 mm grains)

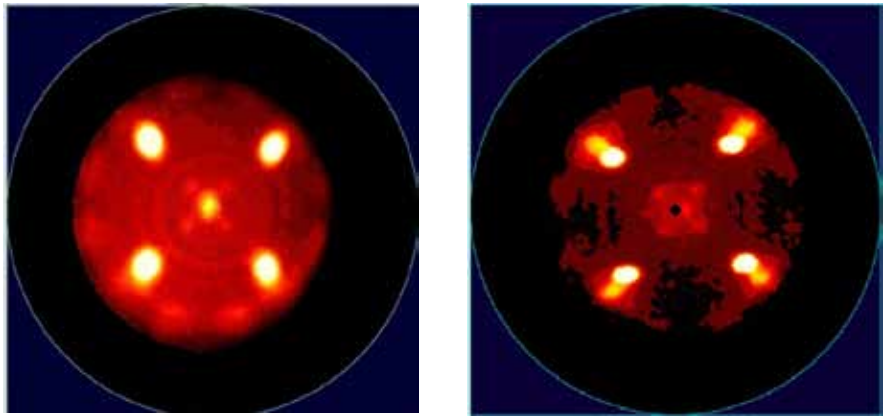


Metallization and Patterning

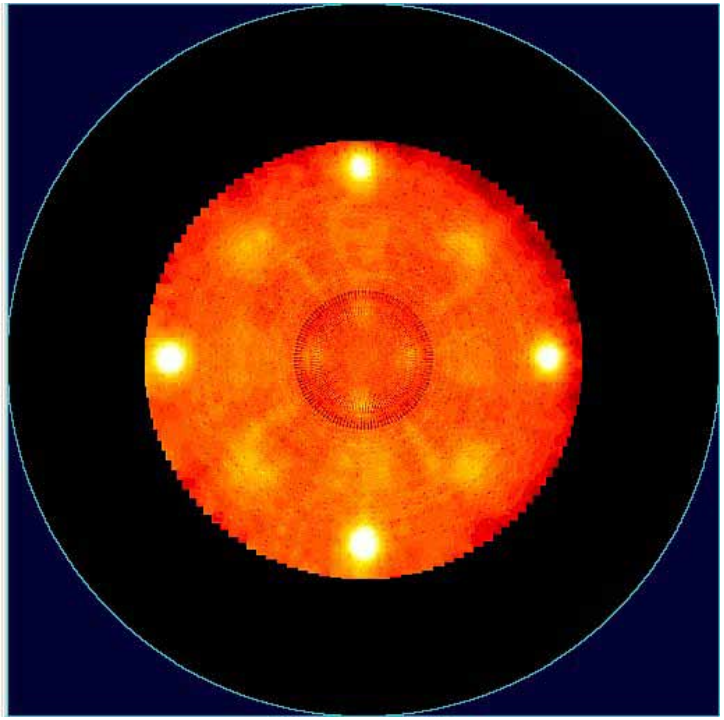






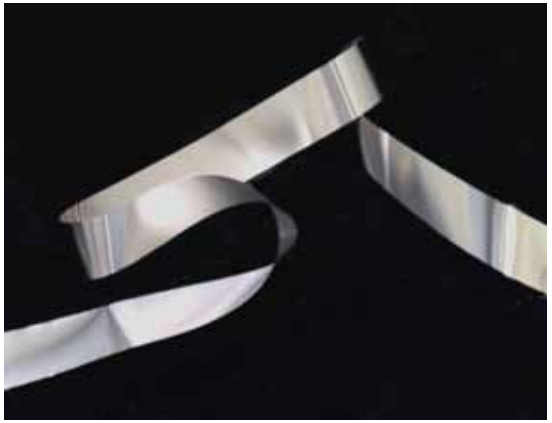


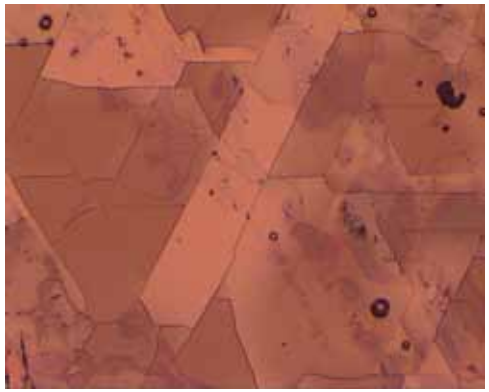
Substrate + Buffers

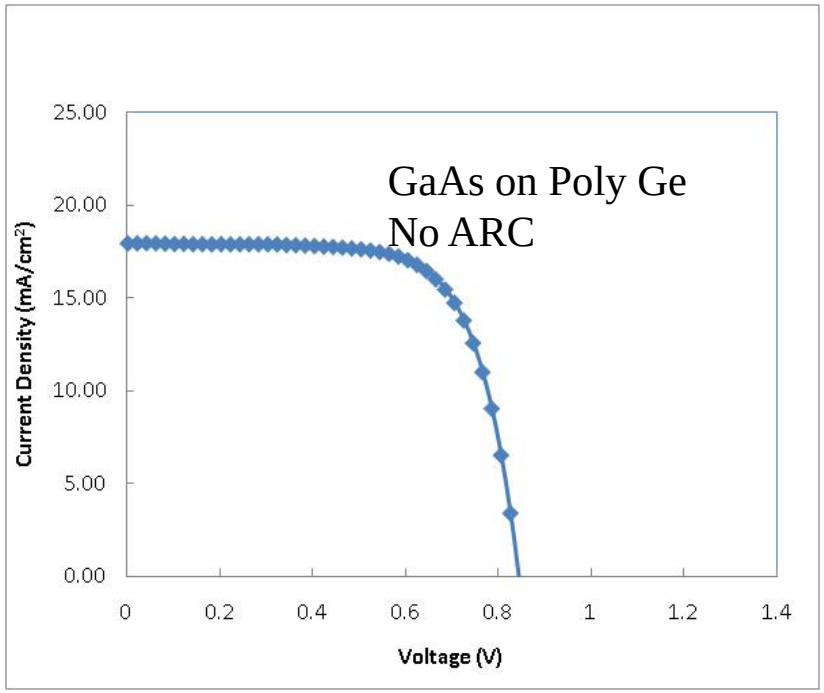


XRD Log Scale Pole Figure of “virtual single substrate” Ge

R2R III-V MJ Development







Courtesty of Wakonda Technologies Inc.

Conclusions

Polycrystalline III-V thin films have the potential for high specific power space solar cells

This approach leverages mature materials system with space heritage and a straightforward path toward multi-junction cells

Polycrystalline III-V solar cells on polycrystalline Ge wafers with 17% 1 sun AM0 performance were demonstrated

Polycrystalline solar cells on recrystallized Ge on 10 mil Mo foil substrates with 3.8% 1 sun AM0 performance were demonstrated

Epi Ge was succesfully grown on large grain and highly textured (in- and out of-plane) 1 mil foil

The Team….

Massachusetts Institute of Technology

Prof. E.A. Fitzgerald
A.J. Pitera
M.L. Lee

Glenn Research Center

D.M. Wilt
P.M. Beck
G.E. Gorecki
E.B. Clark

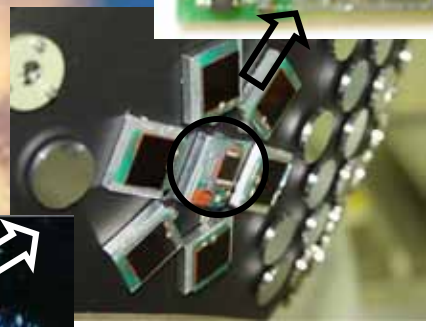
The Ohio State University

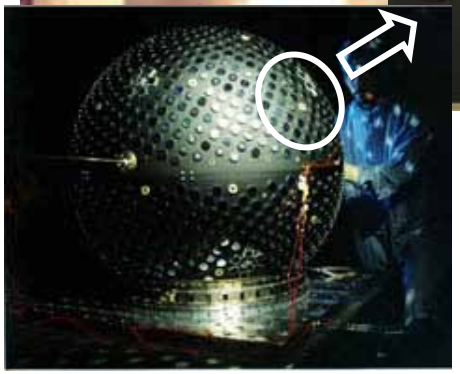
Prof. S.A. Ringel
C.L. Andre
J.A. Carlin
J.J. Boeckl (WPAFB)

M.A. Smith
W.A. Maurer
P.P. Jenkins
D.A. Scheiman

STARSHINE

1in^2 Integrated Micropower System (IMPS)



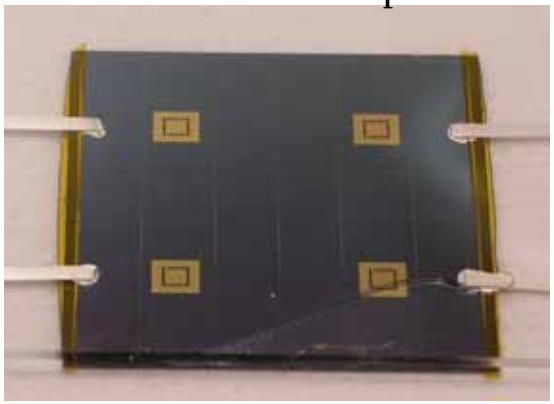


Starshine3 spacecraft (NRL)

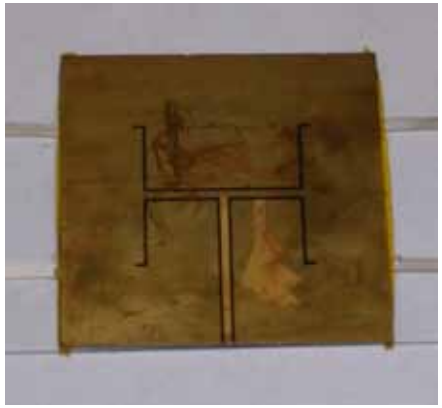
IMPS power system on a chip. These systems were successfully flown aboard Starshine3 and provided continuous power for on-board temperature sensors.

HYBRID SOLAR ARRAY / RF ANTENNA

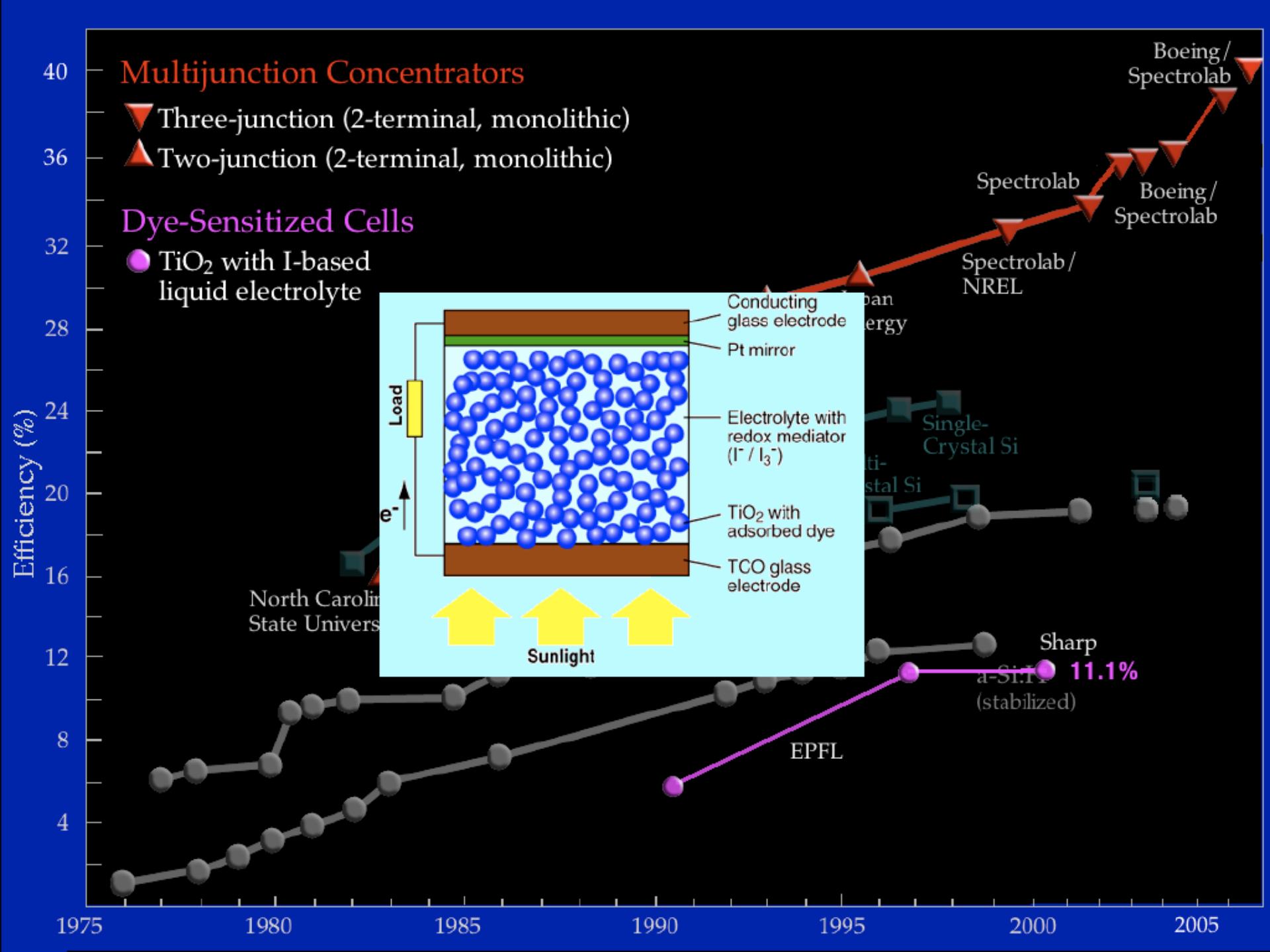
Successfully integrated high efficiency photovoltaics with RF Comm antenna. Provides multi-functional spacecraft surfaces.

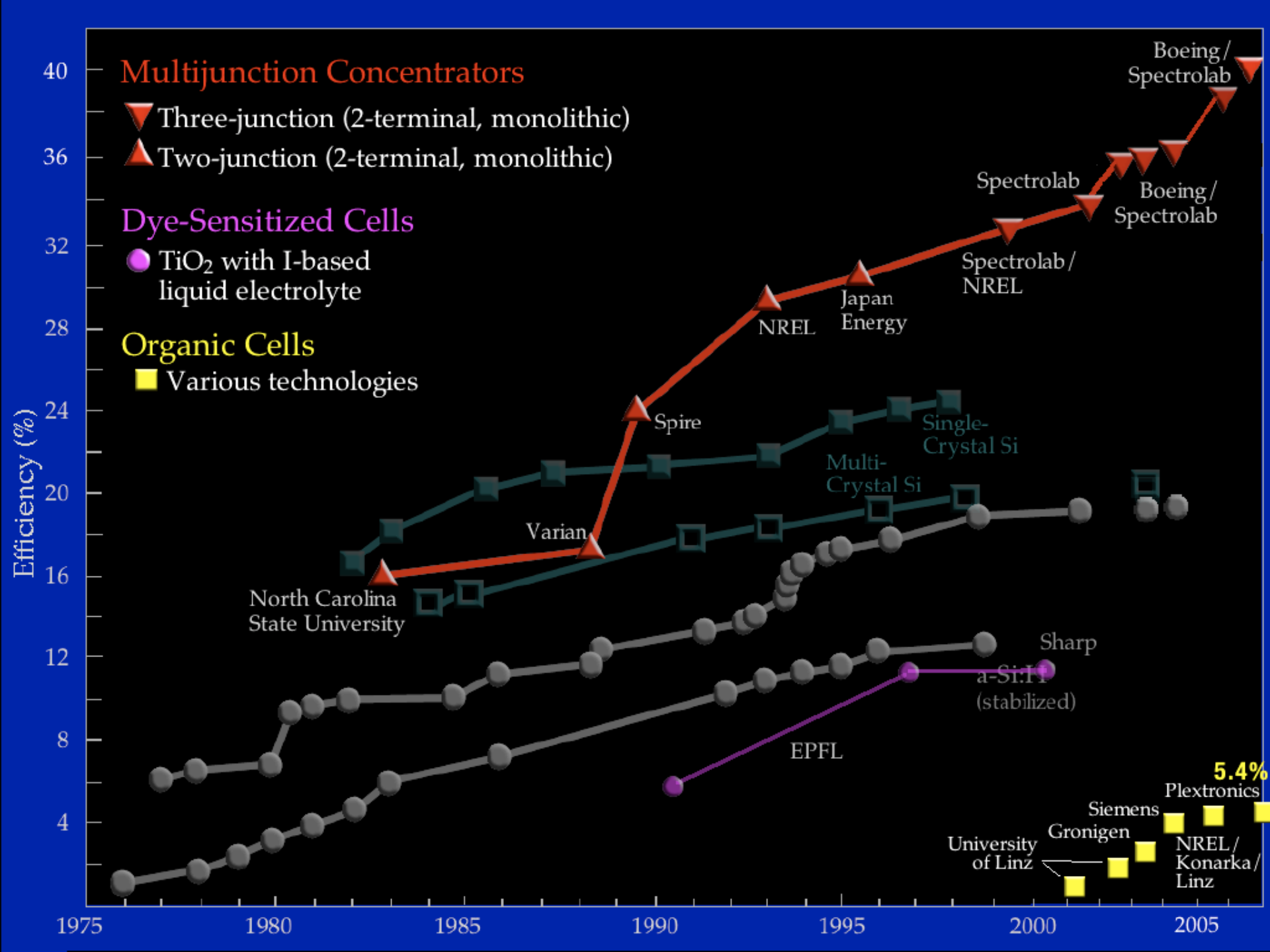


9cm^2 12Vdc Solar Array with Integrated X-Band RF Patch Antennas

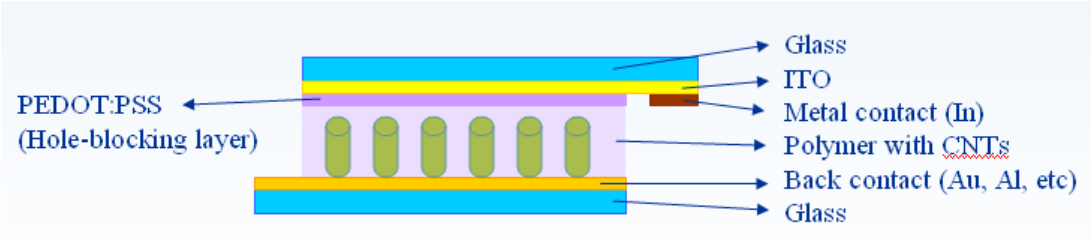


RF Microstrip Feed Network on Rear Surface of Hybrid Solar Array / RF Antenna.

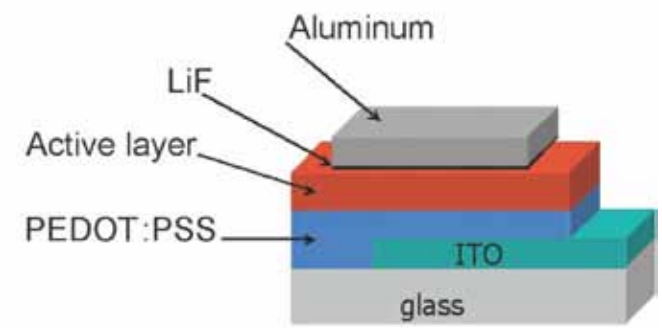

Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO2 with I-based liquid electrolyte
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Single-Crystal Si
Sharp
11.1%
(stabilized)
EPFL
Conducting glass electrode
Pt mirror
Electrolyte with redox mediator (I⁻ / I3⁻)
TiO2 with adsorbed dye
TCO glass electrode
Load
e⁻
Sunlight


Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO2 with I-based liquid electrolyte
Organic Cells
Various technologies
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
Varian
North Carolina State University
Sharp
a-Si:H (stabilized)
EPFL
5.4%
Plextronics
Siemens
Gronigen
University of Linz
NREL / Konarka / Linz

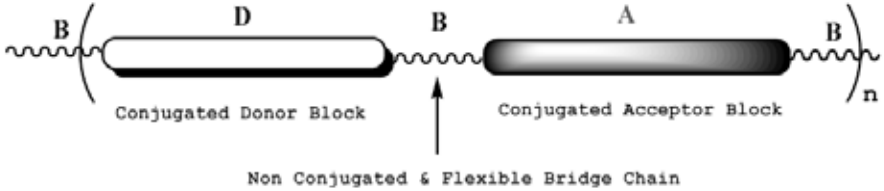
Technology Foundations: Organic Solar Cell Strategies



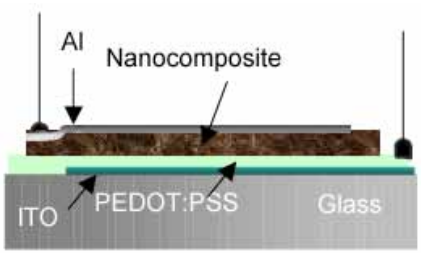
NASA GRC plastic organic/inorganic solar cell utilizing nanotemplate-based fabrication process to significantly increase the cell efficiency by increasing the carrier collection efficiency

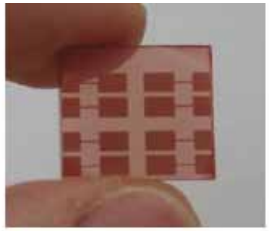


Schematic structure of a typical bulk organic PV device

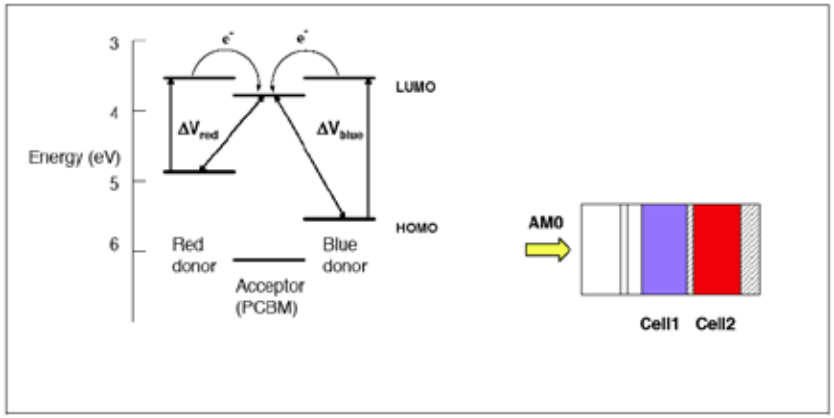


Covalently attached donors and acceptors - Norfolk State (Sun)





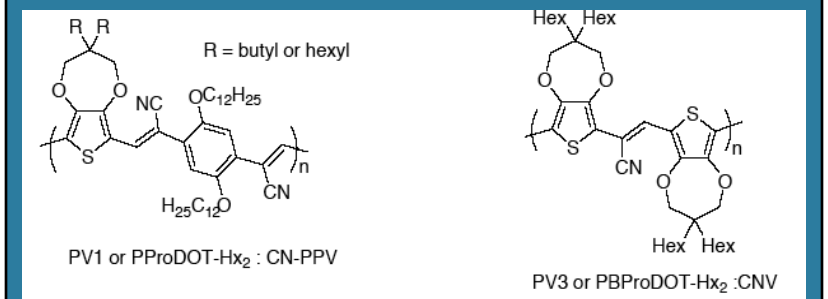
Schematic of the single layer nanocomposite device architecture (left) & image of 3.5 % Nanosys PV cell prototype from Phase I SBIR program (right)



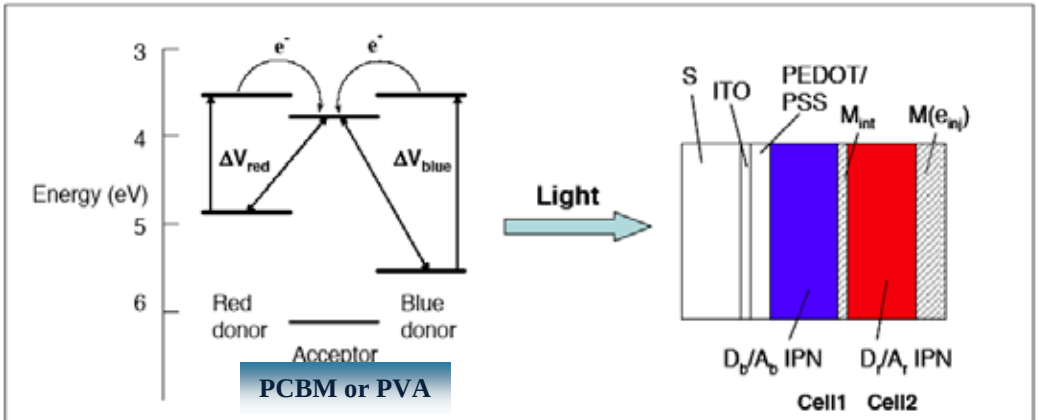
EIC Labs: Design strategy for a two-junction cell

Technology Foundations: EIC 2J-Organic Solar Cell

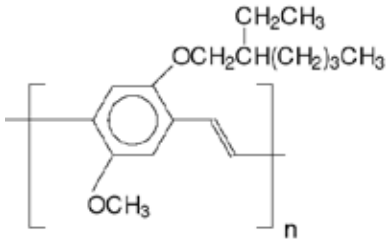
GOAL: Deliver to NASA GRC a 100 cm² IPN solar cell with efficiency near 10%, documented space stability, and a lifetime exceeding 100 hours. Polymer substrate (large-scale, low-temperature manufacturing) with specific power > 1000 W/kg.



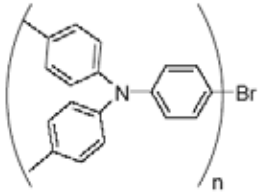
Air-stable red CNV donors (D) produced at UF



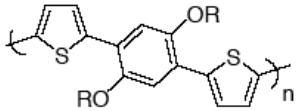
Design strategy for a two-junction cell



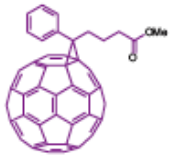
Green MEH-PPV donor (Lit)



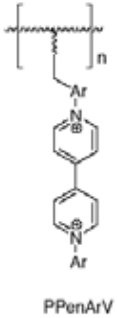
PTPA purple donor (EIC)



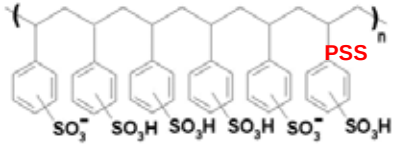
Blue PBTB-(OR)$_2$ donor (UF)

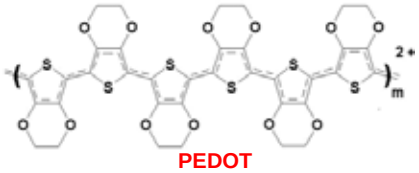


PCBM acceptor (A) (Lit)



Poly-viologen acceptor (A') (UF)



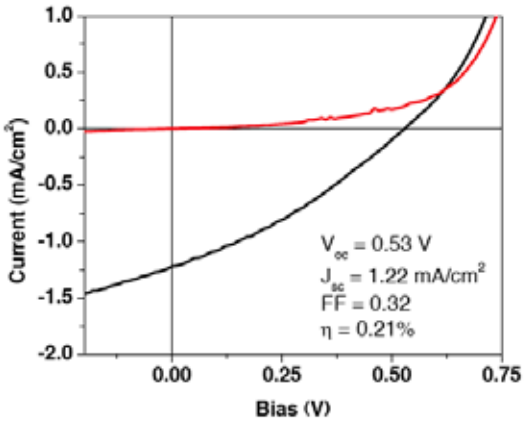


$PEDOT^+ + PSS^- + M^+ + e^- \rightleftharpoons PEDOT^0 + M^+PSS^-$

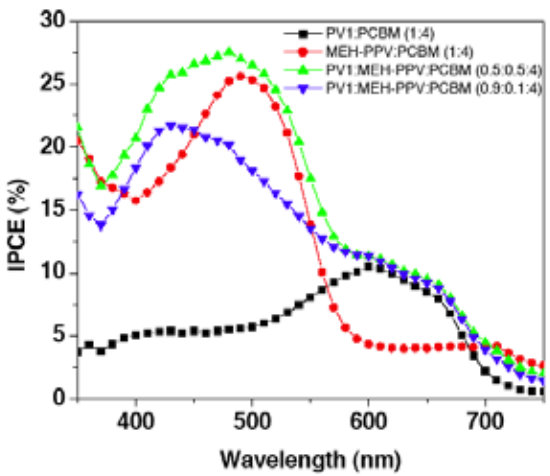
Technology Foundations: EIC 2J-Organic Solar Cell cont.

PHASE II PROGRAM OVERVIEW

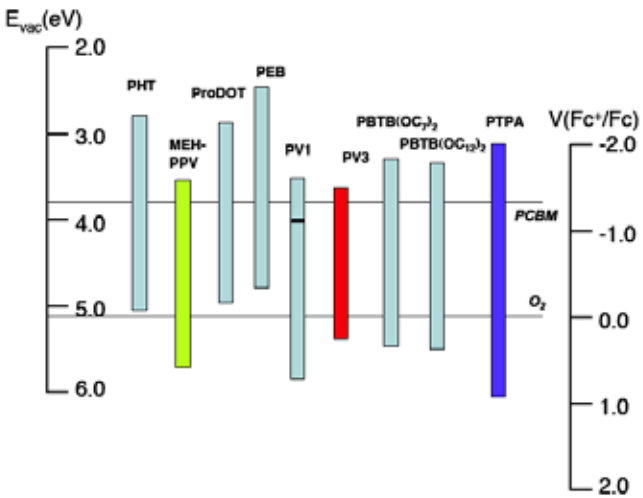
- Continued development of controlled bandgap high mobility donor and acceptor polymers; final selection of high, middle, and low-bandgap absorbers (UF)
- Development of maximized single-junction high-efficiency IPN-type cells from new polymers with conversion efficiency > 4% for each component (EIC)
- Optimized stacked cells, focus on interfacial regions and individual layer deposition methods, goal being 10% efficiency (EIC)
- Space environmental testing and characterization (illumination, vacuum, and thermal cycling) with submission of cells for AM0 testing (UF/EIC)
- Scale-up of best cells to 100 cm^2 and delivery of best cells to NASA GRC (EIC)



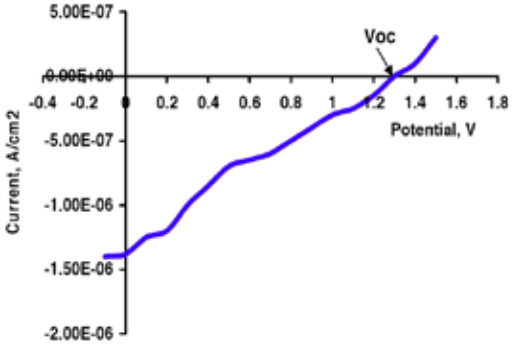
IV curve of PV3:PCBM IPN solar cell under AM1.5 irradiation



Spectral analysis of red, green, and blue polymer absorbers and PCBM donor



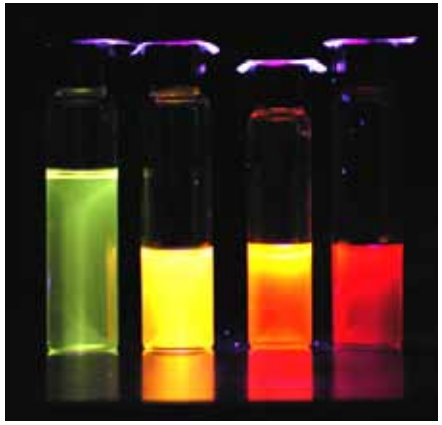
HOMO/LUMO energy levels and bandgaps of donor polymers on a vacuum energy scale and an electrochemical scale; also shown are the LUMO energy levels of the fullerene-type acceptor PCBM and of O_2.



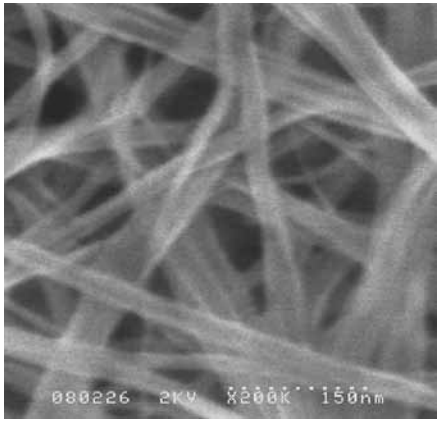
IV curve of two-junction cell comprising ITO|PEDOT/PSS|PTPA/PCBM|Ag|PV1/PCBM|Al; note increase of Voc.

Nanomaterials for Polymeric PV

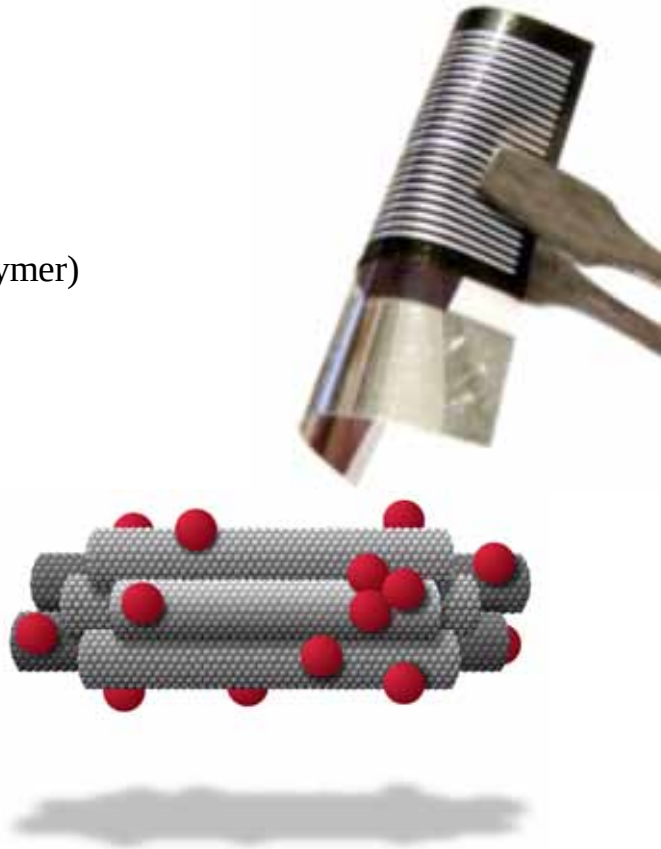
- High electron affinity for polymer exciton dissociation
- SWNTs have extremely high electrical conductivity
- Optical absorption properties which can be tuned by size
- SWNTs have tremendous aspect ratio (low percolation threshold in polymer)



CdSe Quantum Dots

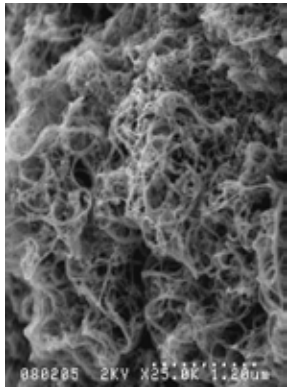


Single Wall Carbon Nanotubes (SWNTs)

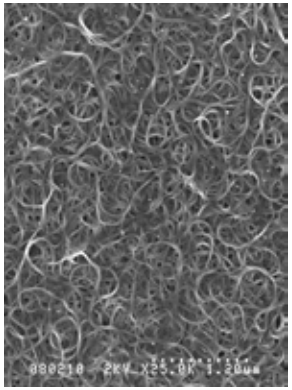


QD-SWNT Complex

Raw

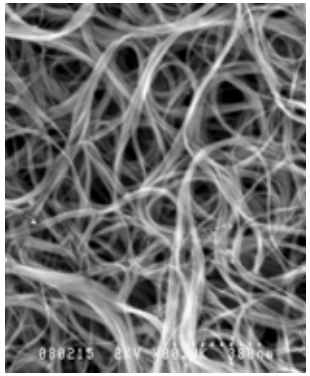


Acid Reflux

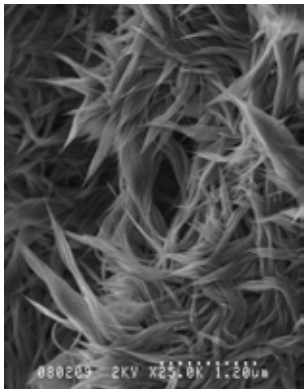


Oxygen

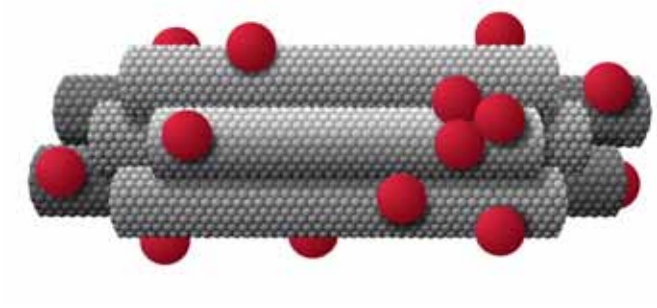
Purified



Cut



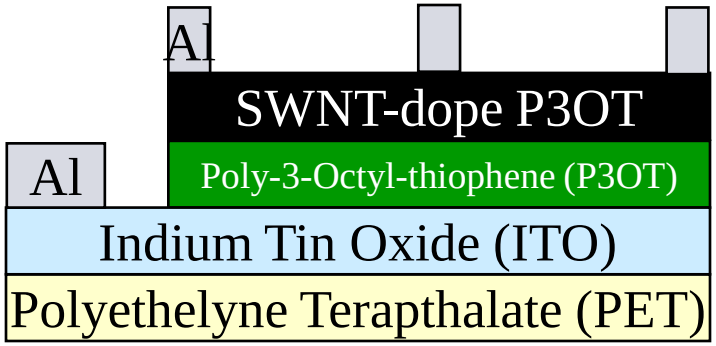
Quantum Dot Attachment



Flexible Thin Film Cell

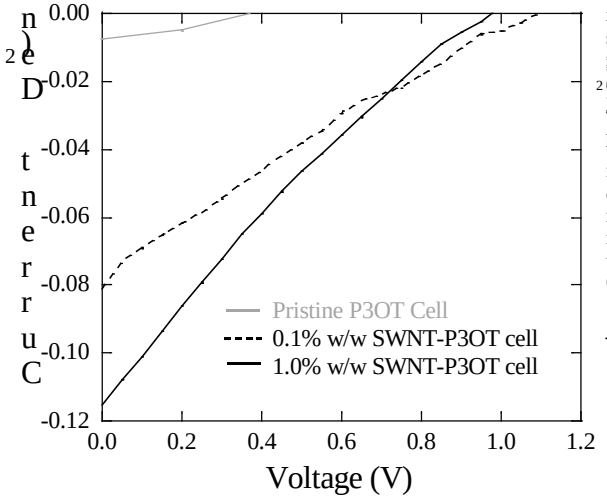
SWNT-Polymer Solar Cells

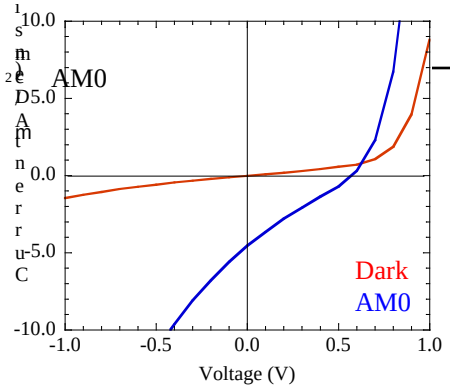
Device Configuration



Results [1]

- SWNTs have extremely high electrical conductivity and sufficient electron affinity to dissociate polymer excitons
- SWNTs exhibit low percolation threshold in polymer and enhancement in I_{sc} at a low percent doping level



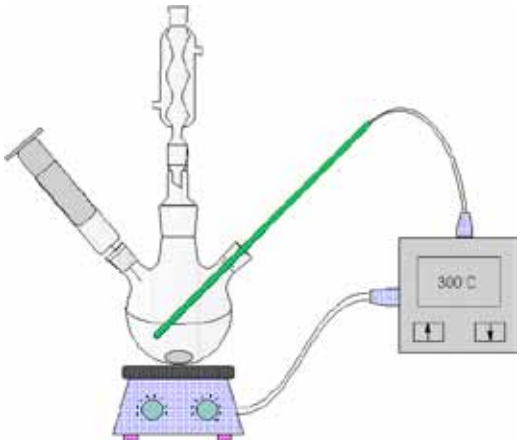


	V_{oc} (V)	I_{sc} (mA/cm^2)
P3OT	0.35	0.01
0.1% SWNTs	1.05	0.08
1.0% SWNTs	0.98	0.12

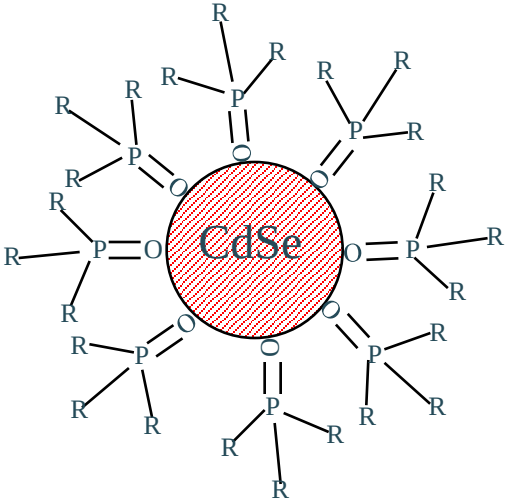
[1]B.J. Landi, R.P. Raffaelle, S.L. Castro, S.G. Bailey, Prog. Photovot: Res. Appl. (2005).

Colloidal Synthesis of Quantum Dots

Colloidal Synthesis of QDs

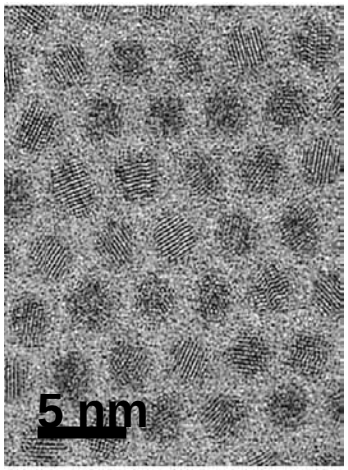


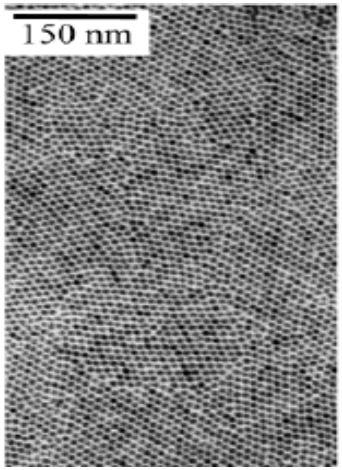
Surface Chemistry



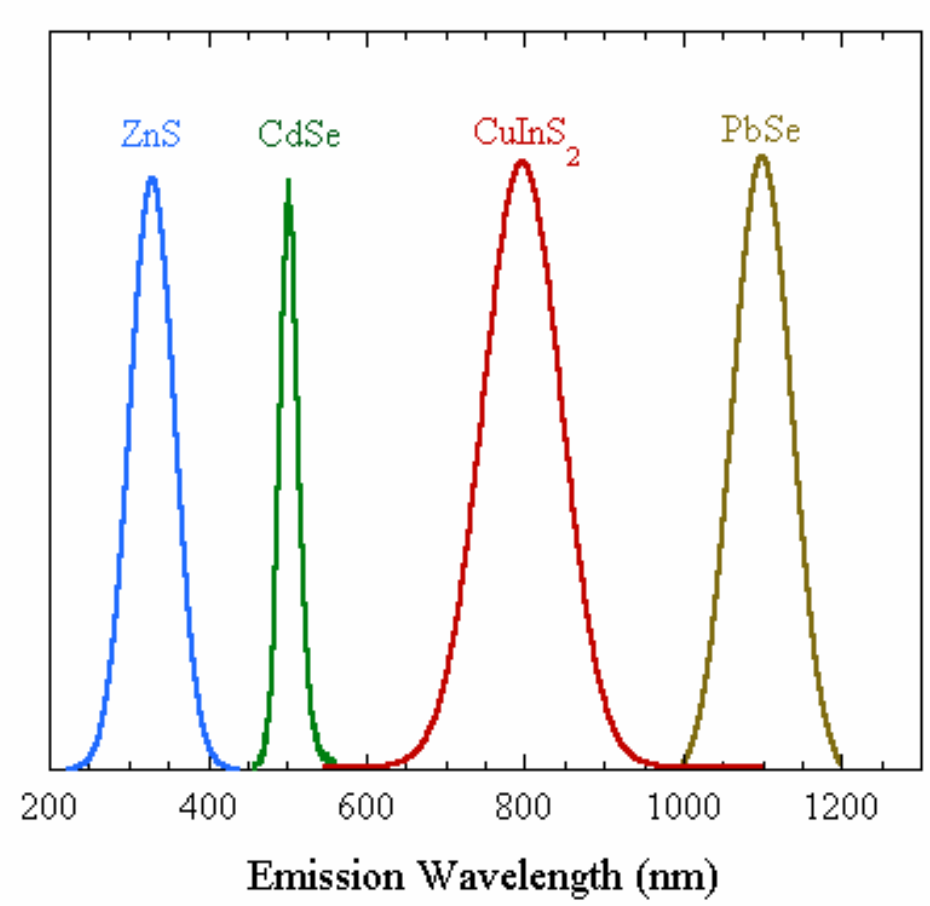
Quantum Dot Extraction

TEM





Compositional Tunability

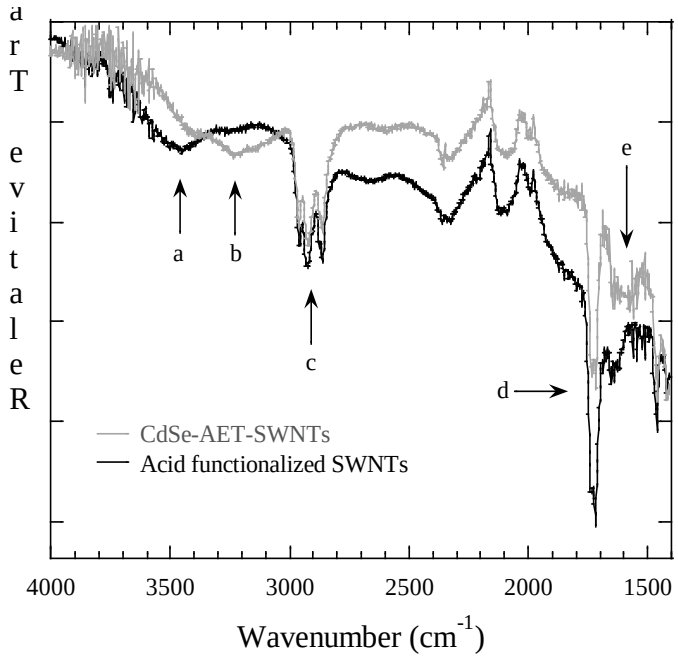


<u>Tunability for Semiconducting QDs</u>

ZnS: 280-350 nm
CdSe: 450-700 nm
$CuInS_2$: 650-750 nm
PbS: 700-1600 nm
PbSe: 1100-3000 nm

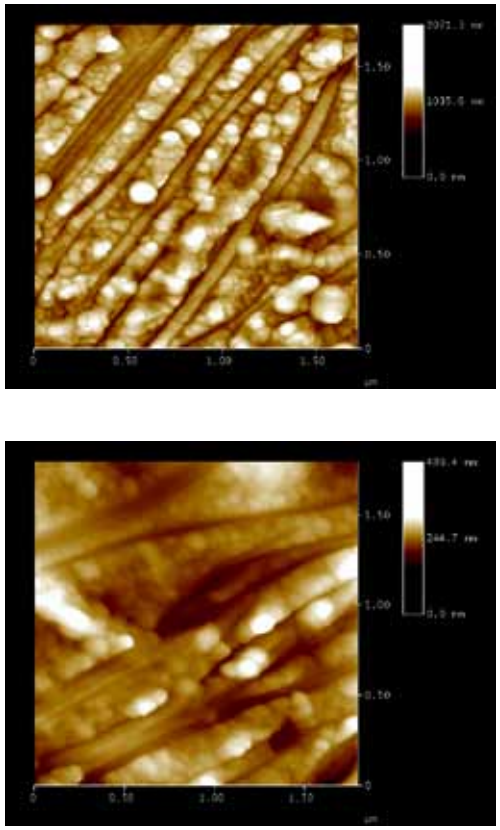
CdSe-AET-SWNT Complex Characterization

FT-IR Spectroscopy

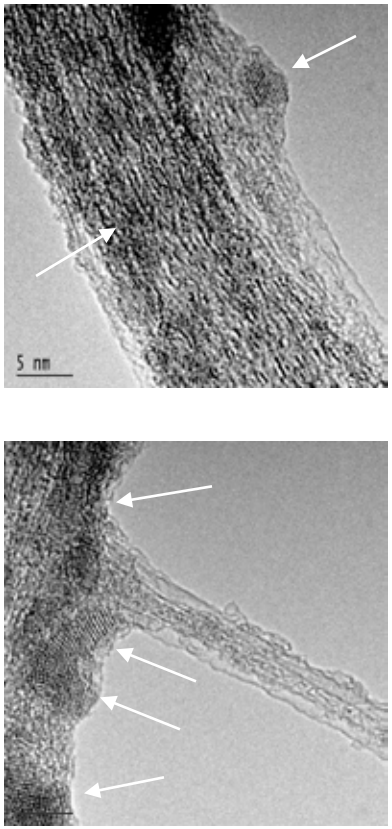


Peak	Region (cm^{-1})	Band Assignments[34]
a	3468	_OH stretch for carboxylic acid
b	3232	_CO_NH_R stretch in amide
c	2857_2925	_C_H stretch
d	1715	_C=O stretch for carboxylic acid
e	1550_1650	_N_H bend, _C= O stretch for amide

Microscopy

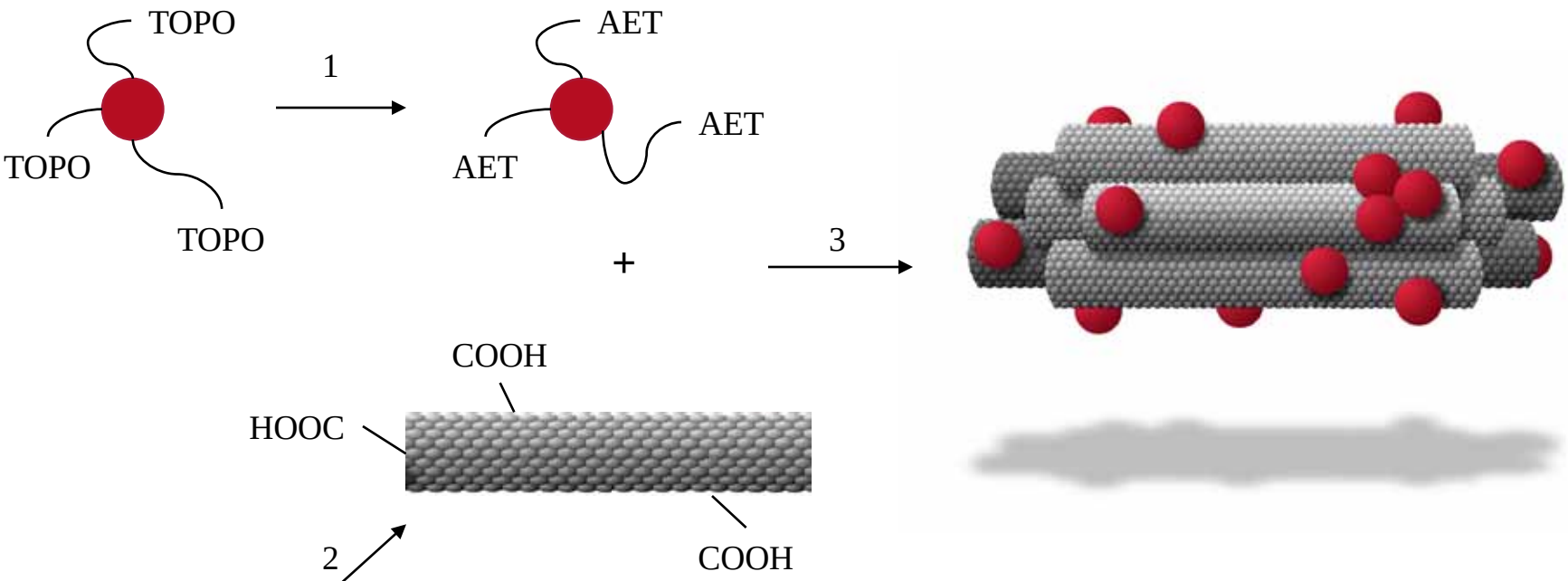


AFM

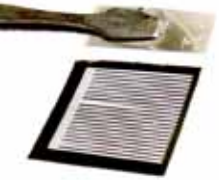


TEM

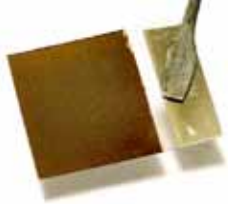
QD-SWNT Complex Synthesis



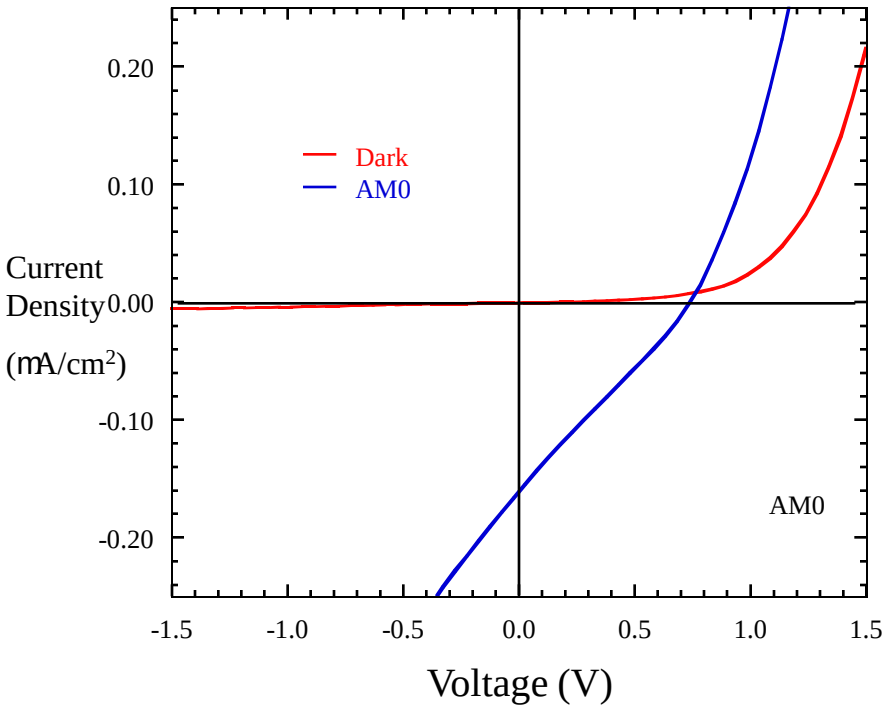
1. *QD ligand exchange*
   - Stir CdSe-TOPO in neat aminoethanethiol (AET) for 24 hrs
2. *Acid-functionalization of SWNTs*
   - Ultrasonication in 4:1 mixture of concentrated H_2SO_4:H_2O_2 for 2.5 hrs
3. *Covalent coupling*
   - Activation with EDC/sNHS and stir in DMF for 2 hrs



IV data for CdSe-AET-SWNT-P3OT



Photoresponse

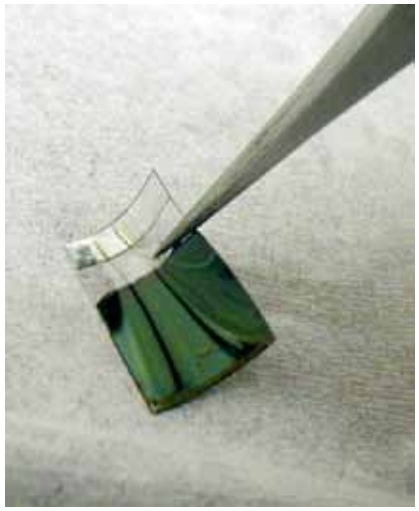


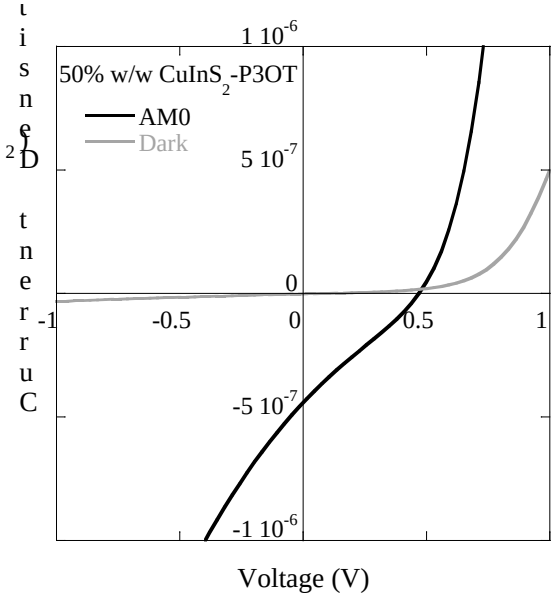
- Spray deposition of composite onto ITO-PET and thermal evaporation of aluminum contacts
- Diode observed under 1 Sun AM0 illumination
- Lower efficiency attributed to the carrier traps from the amorphous carbon impurities in the complexes during functionalization

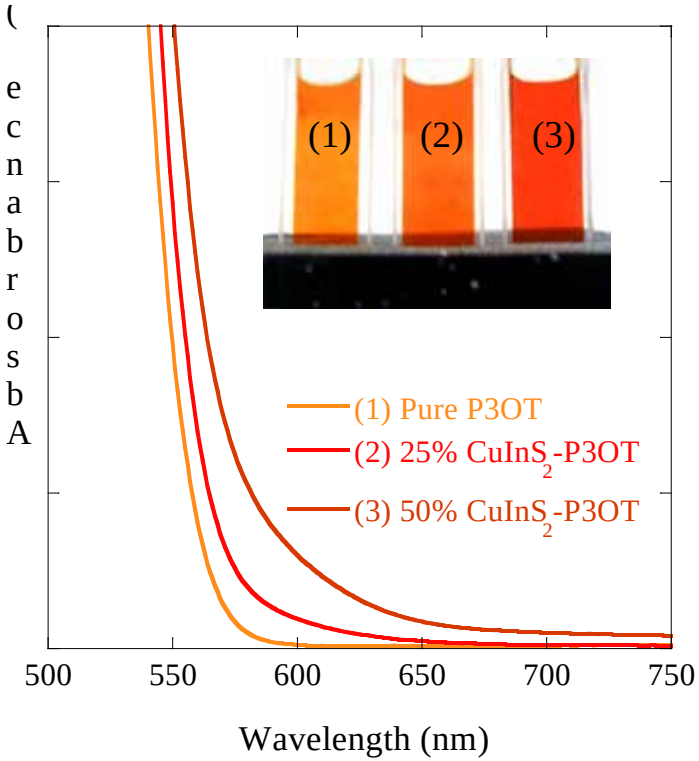
	V_{oc} (V)	I_{sc} (mA/cm^2)
Dark	0.30	0.001
AM0	0.75	0.16

$CuInS_2$-Polymer Solar Cells

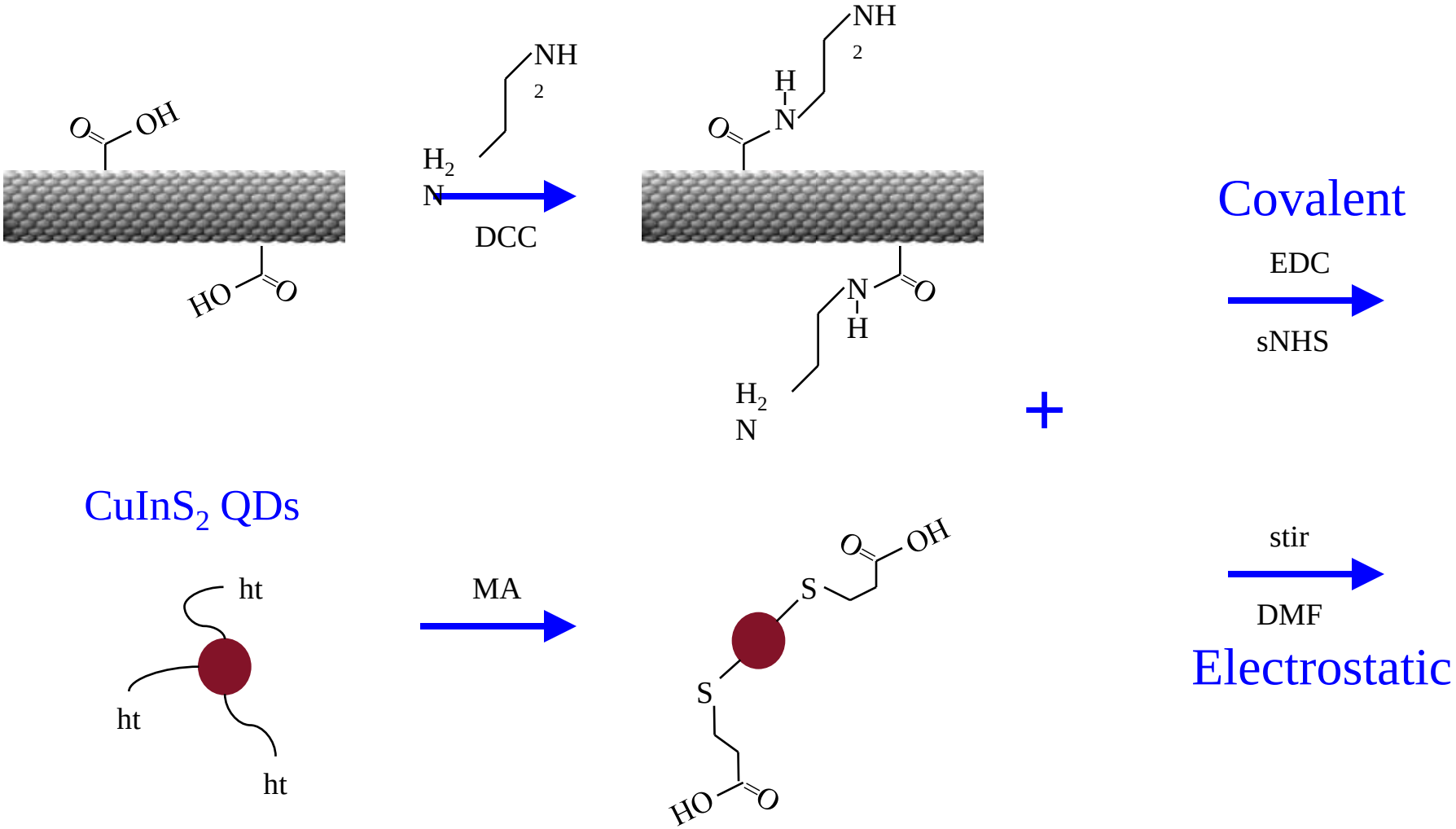
Device Configuration



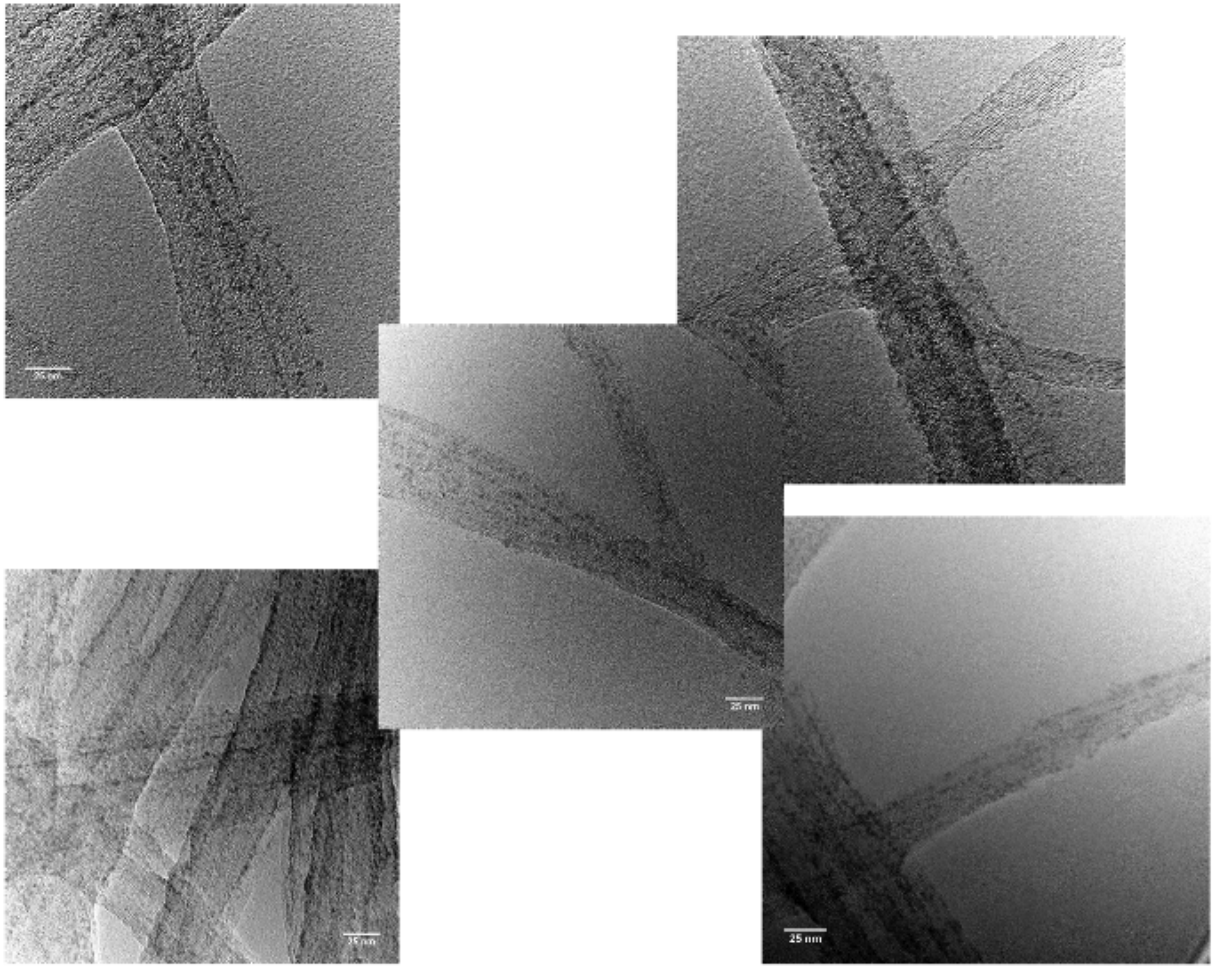




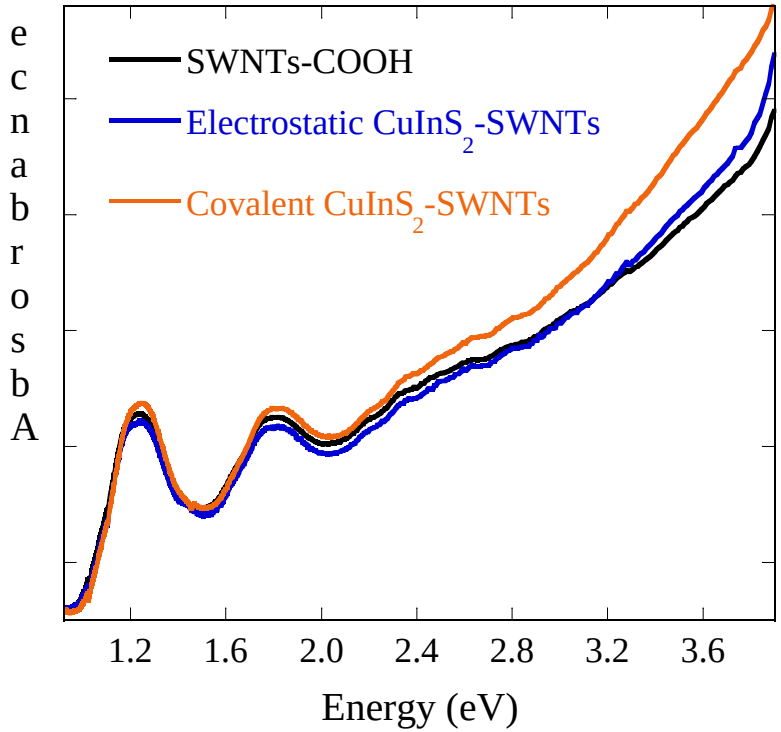
$CuInS_2$-MA-en-SWNT Complex Synthesis



Electrostatically Bonded $CuInS_2$ QDs on SWCNT



Optical Absorption Spectroscopy



- 10 meV blue-shift in *covalent* $CuInS_2$-MA-en-SWNT complex *only*
- Increased absorption above 2 eV more dominant in covalent product

CONCLUSIONS

- Nanomaterials offer the ability for synthetic “tuning” of properties to better promote exciton dissociation and carrier transport in polymeric PV
- Energy level diagrams indicate that enhancement in AM0 spectral absorption and carrier transport may be best with QD-SWNT-Polymer devices
- Synthesis schemes have been outlined for covalent and electrostatic attachment of CdSe and $CuInS_2$ quantum dots to SWNTs
- Characterization of CdSe-AET-SWNT complexes with AFM, TEM, FT-IR, and Raman spectroscopy showed successful covalent attachment and potential charge transfer
- Characterization of $CuInS_2$-MA-en SWNT complexes suggests that covalent attachment was successful while electrostatic attempts proved ineffective
- Future work includes fabrication of polymeric devices incorporating QD-SWNT complexes to mimic energy level cascade

Technololgy Investment Pathways

Basic Research Driven

Fundamental Science

3rd Generation PV

- quantum dots
- nanotechnology
- multi-multijunctions
- thermophotonics
- intermediate band
- bio-inspired

Revolutionary
(15 years and beyond)

Industry-Driven

Applied Science & Technology

1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

Accelerated Evolutionary
(3-5 years)

Disruptive
(5-15 years)

Technology-Driven

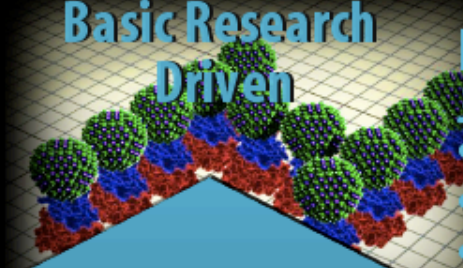
Transformational Science & Technology

2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%

Technololgy Investment Pathways

Basic Research Driven



Fundamental Science

3rd Generation PV

- quantum dots
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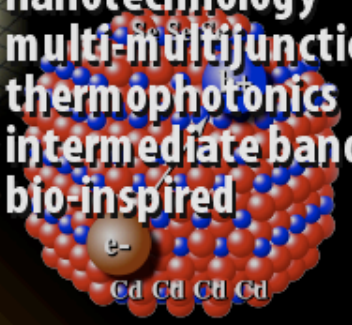
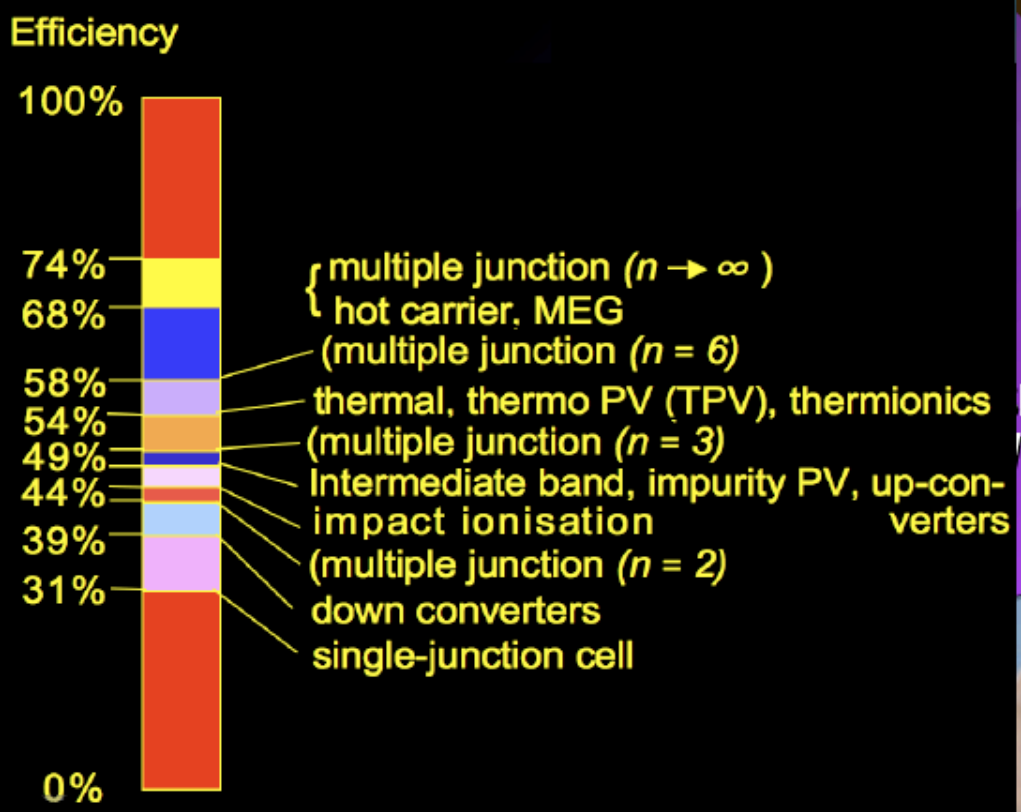
- thermophotonics
- intermediate band
- bio-inspired



Revolutionary

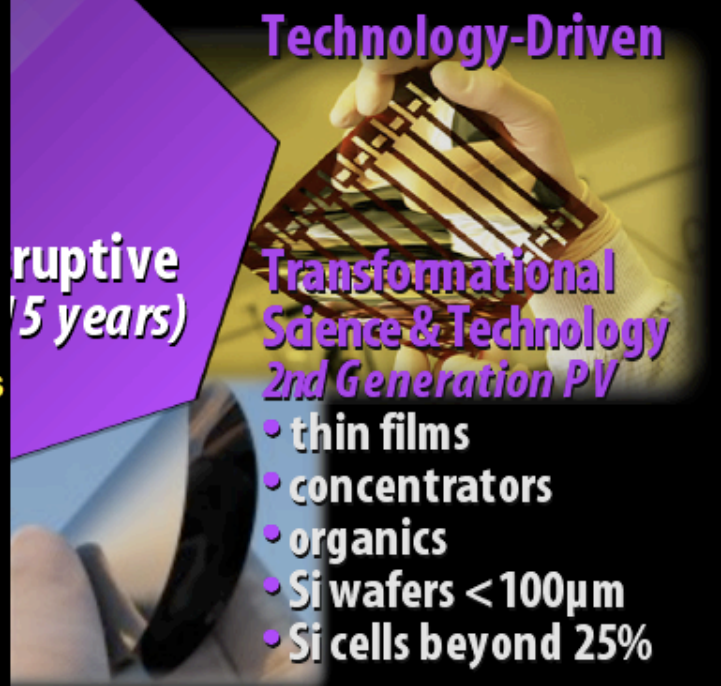
(15 years and beyond)



ruptive

5 years)

Technology-Driven



Transformational Science & Technology

2nd Generation PV

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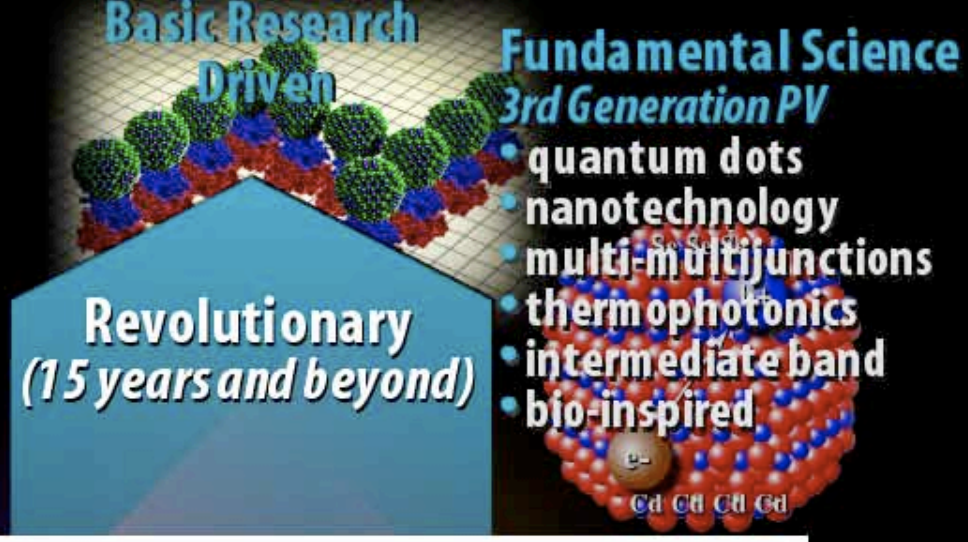
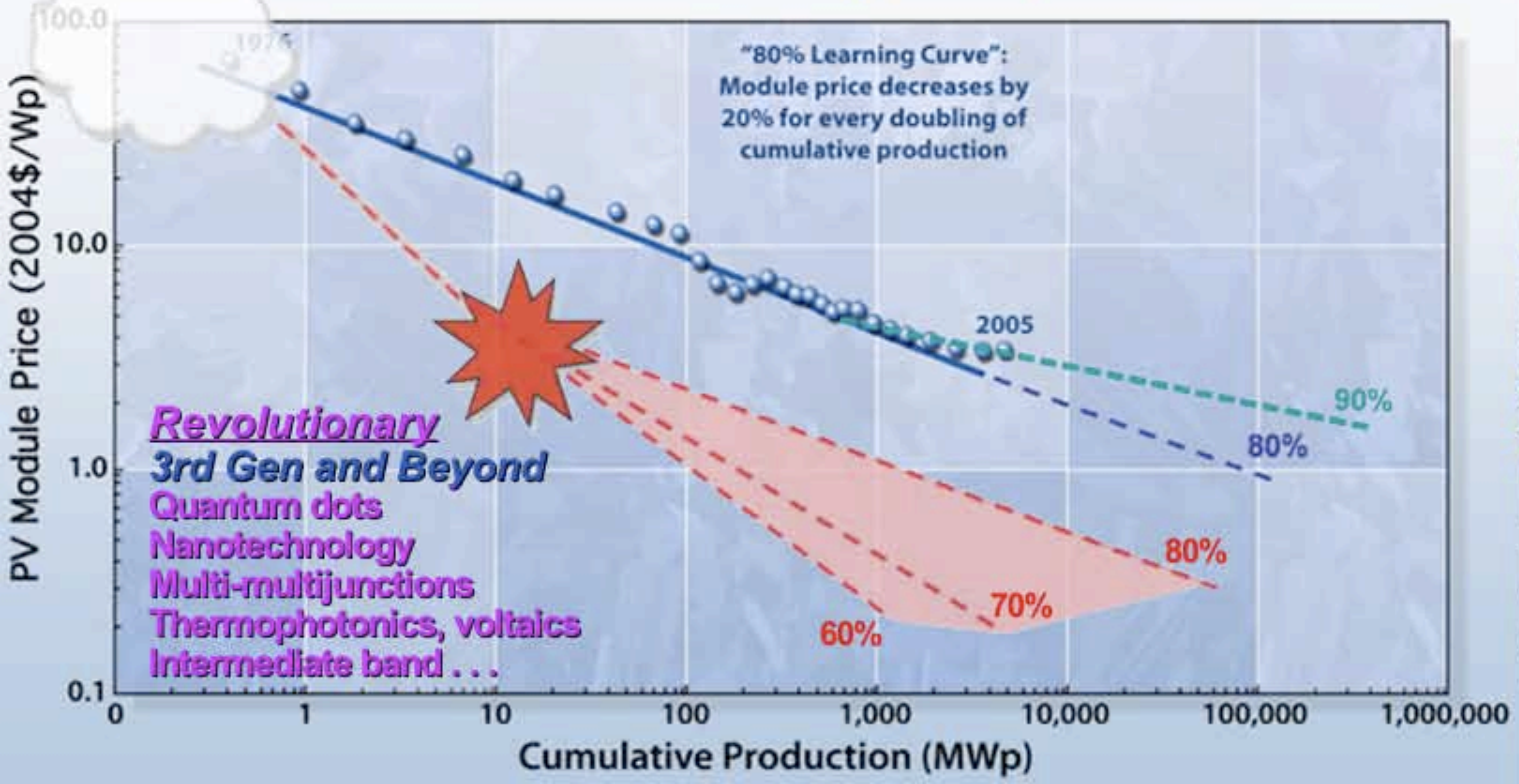
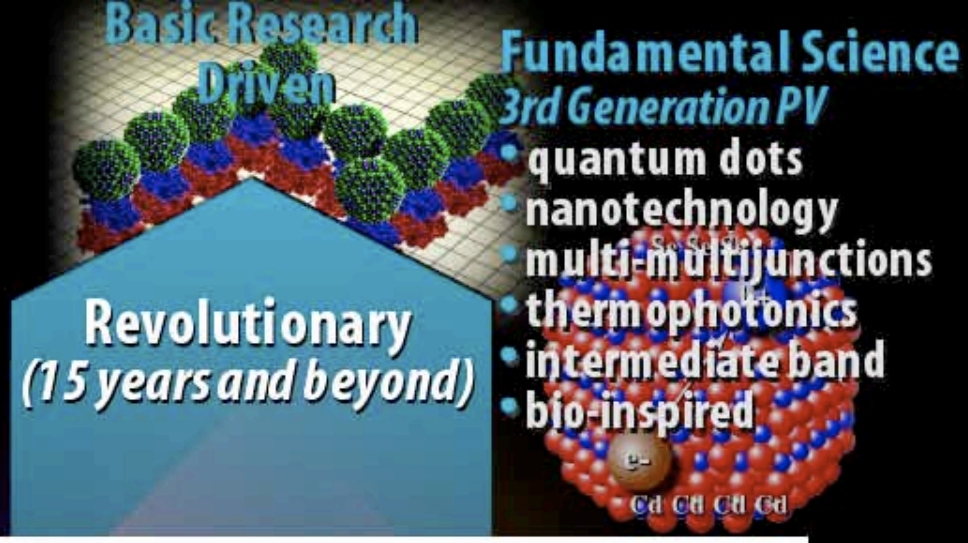
Technololgy Investment Pathways



Module Production Learning or Experience Curve



Technololgy Investment Pathways



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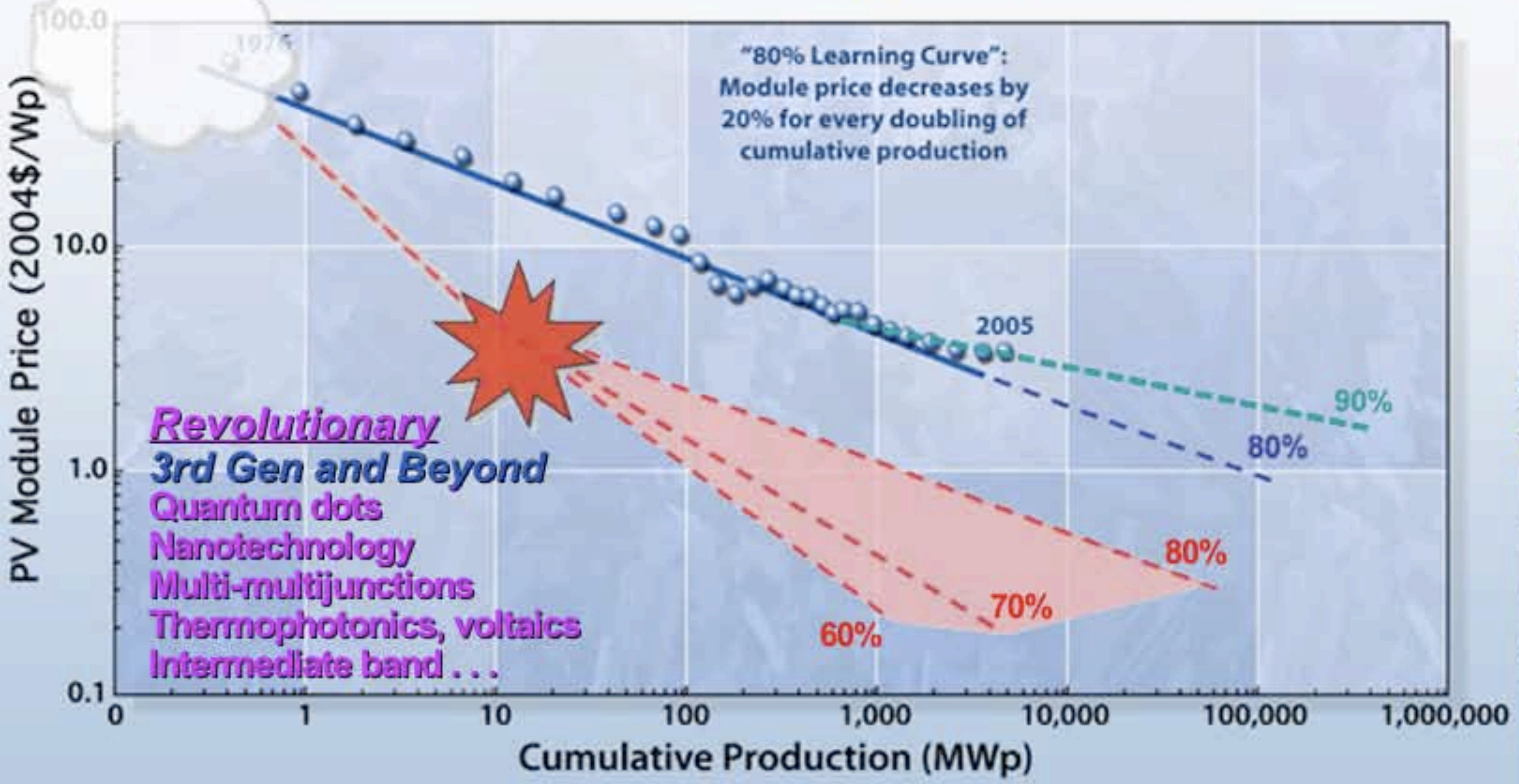

hnology-Driven

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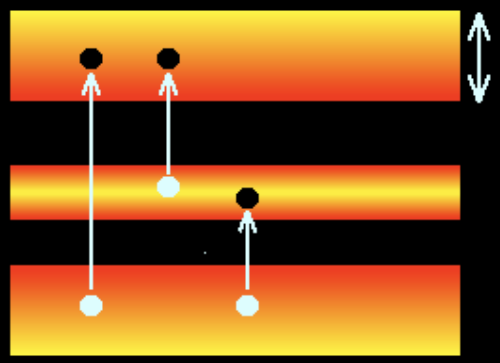
3rd, 4th, . . . Future Generations

Revolutionary Technologies for Our Next Generations of Consumers

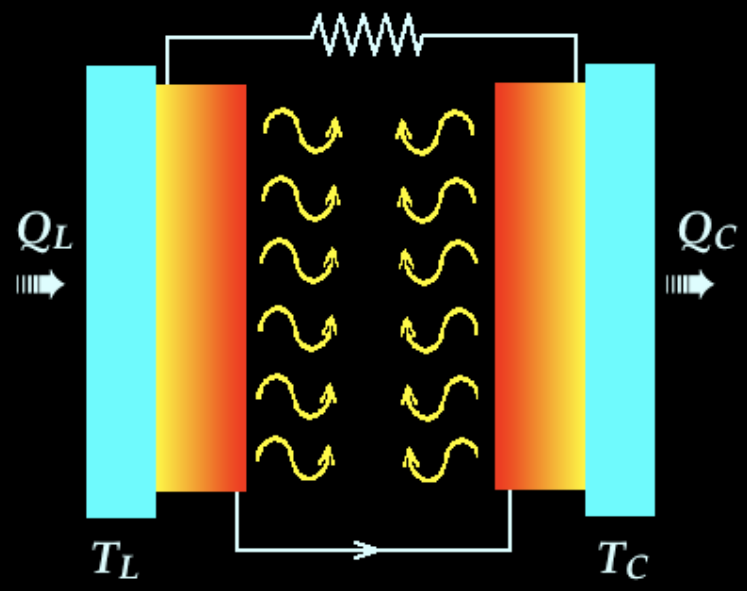
. . . quantum dot, pod, rod and other novel structures; nanotechnologies; multiple-junctions...
with efficiencies 2-3 *times* those for conventional PV

. . . high-risk research

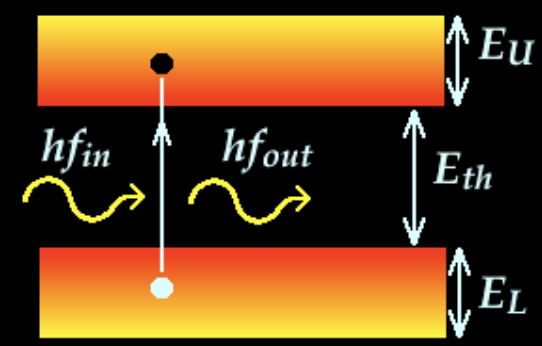
. . . the fringes of technology exploration



Multiband Cells



Thermophotonic and Thermophotovoltaic Conversion



Multiple Electron-Hole Pairs

3rd, 4th, . . . Future Generations

Revolutionary Technologies for Our Next Generations of Consumers

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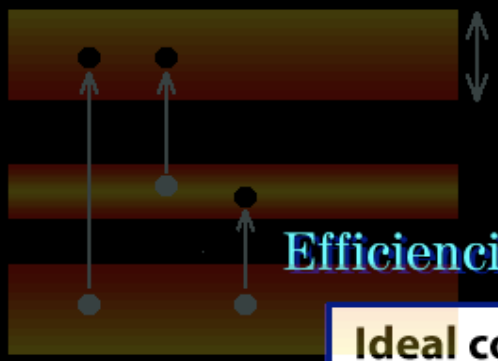
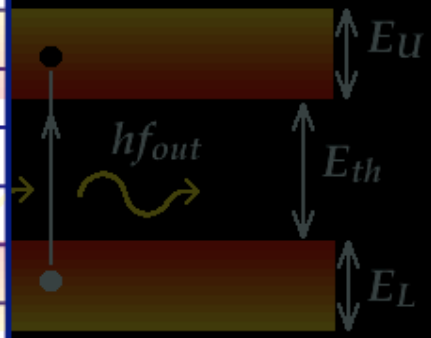
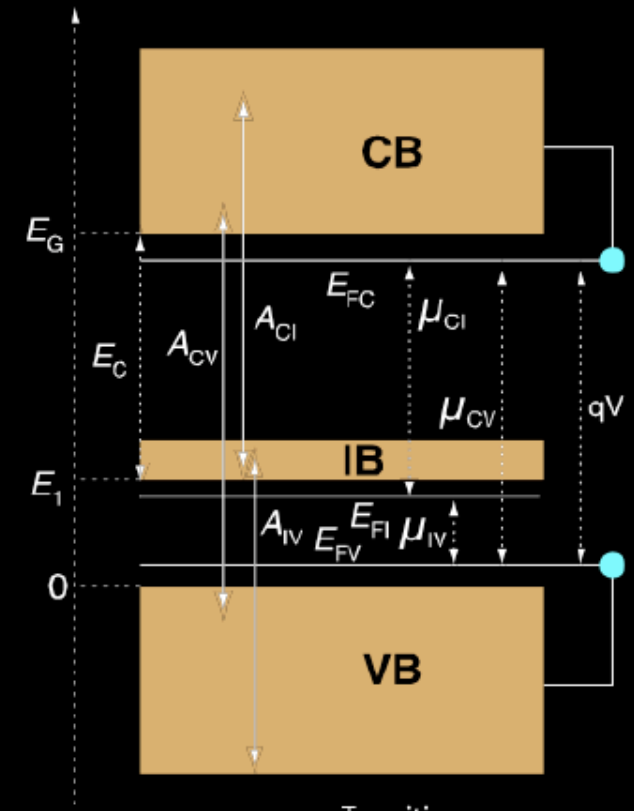


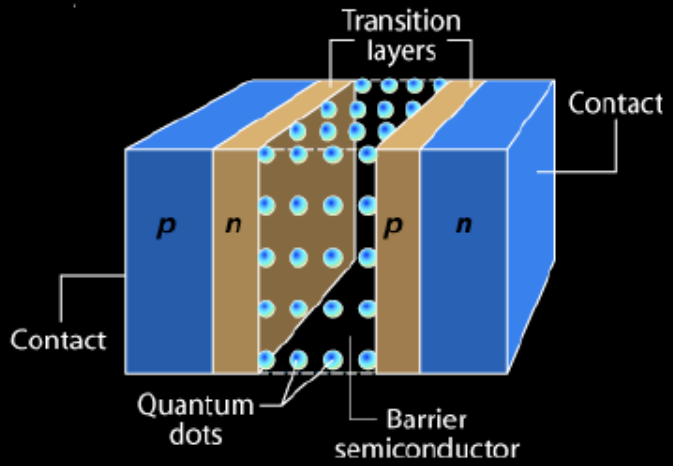
Efficiencies for Ideal Future Generation Solar Cells

Ideal converter; T_S = 6000K, T_a = 300K isotropic illumination	Efficiency
Carnot	0.950
Landsberg	0.933
Multijunction	0.868
Impact ionisation, best Q	0.868
Solar thermal	0.854
Hot electrons	0.854
Thermophotovoltaic	0.854
Thermophotonic	0.854
Intermediate band, (MQD or alloy)	0.632
2nd photon pumped MQW	0.632
Shockley & Queisser limit	0.403



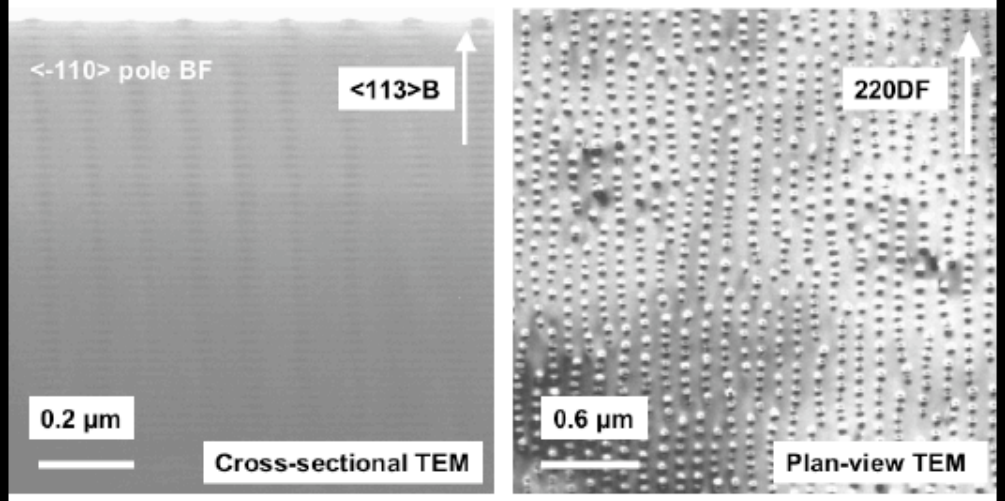
Intermediate Band Solar Cells





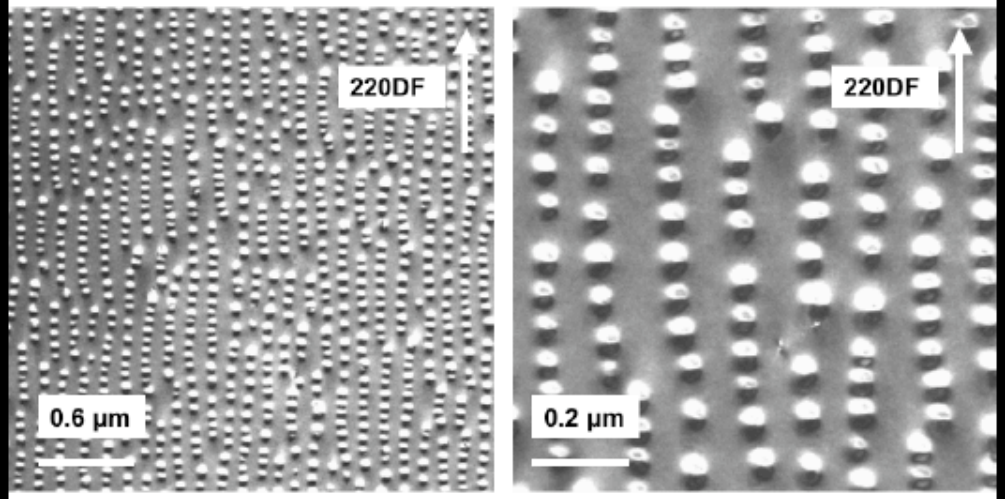
A. Norman, M Romero, and M. Al-Jassim, (NREL), A. Luque, A. Marti, Spain

MOCVD Growth of InGaAs/GaAs QD arrays on (113)B GaAs substrates for intermediate band solar cells



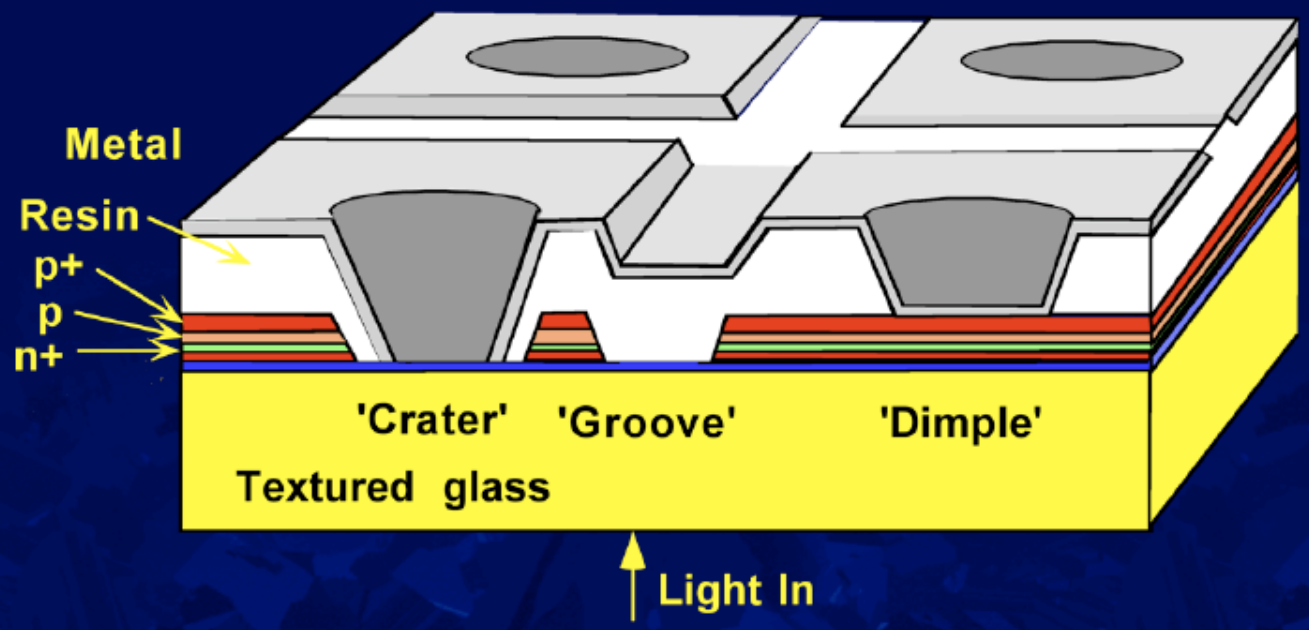
- QD arrays are being grown to test concept of intermediate band solar cell proposed by A. Martí and A. Luque

(311)B 50 period InGaAs/GaAs QD superlattice plan-view TEM



- Chains of quantum dots along <110>

Polycrystalline Thin Film



CSG Solar approach

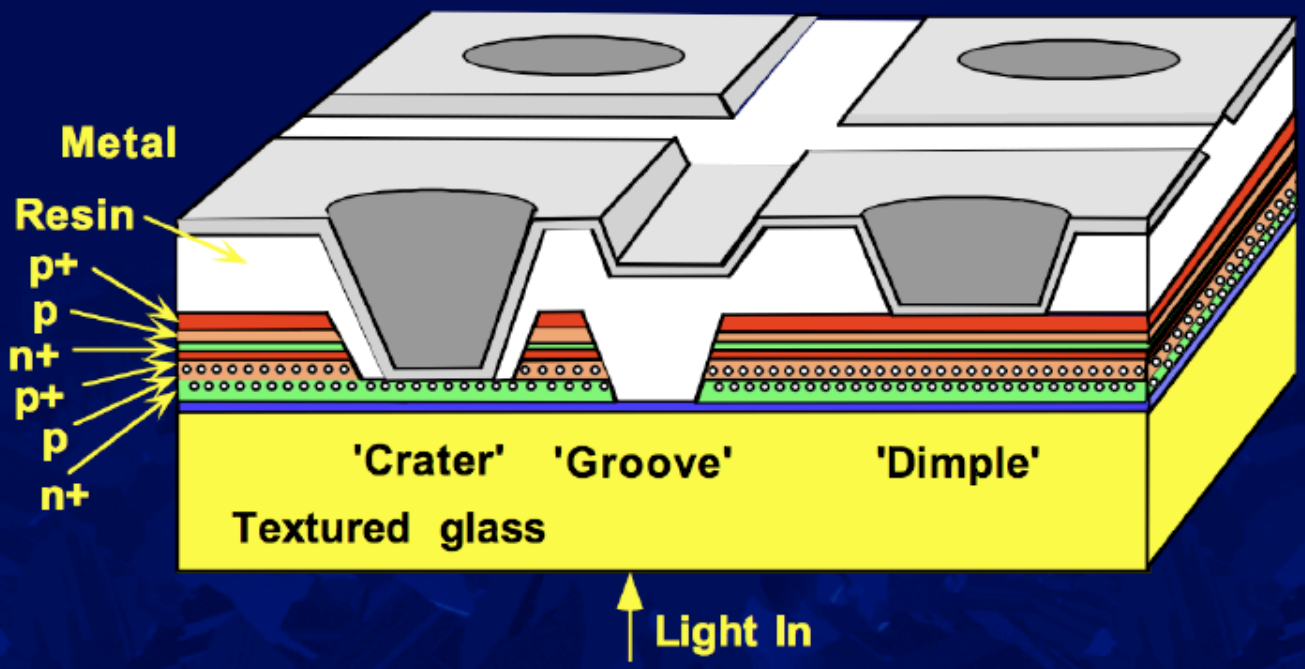
. high-T silicon

. high-density contacts

. good optics

. deposit then process

Polycrystalline Thin Film



CSG Solar approach

. high-T silicon

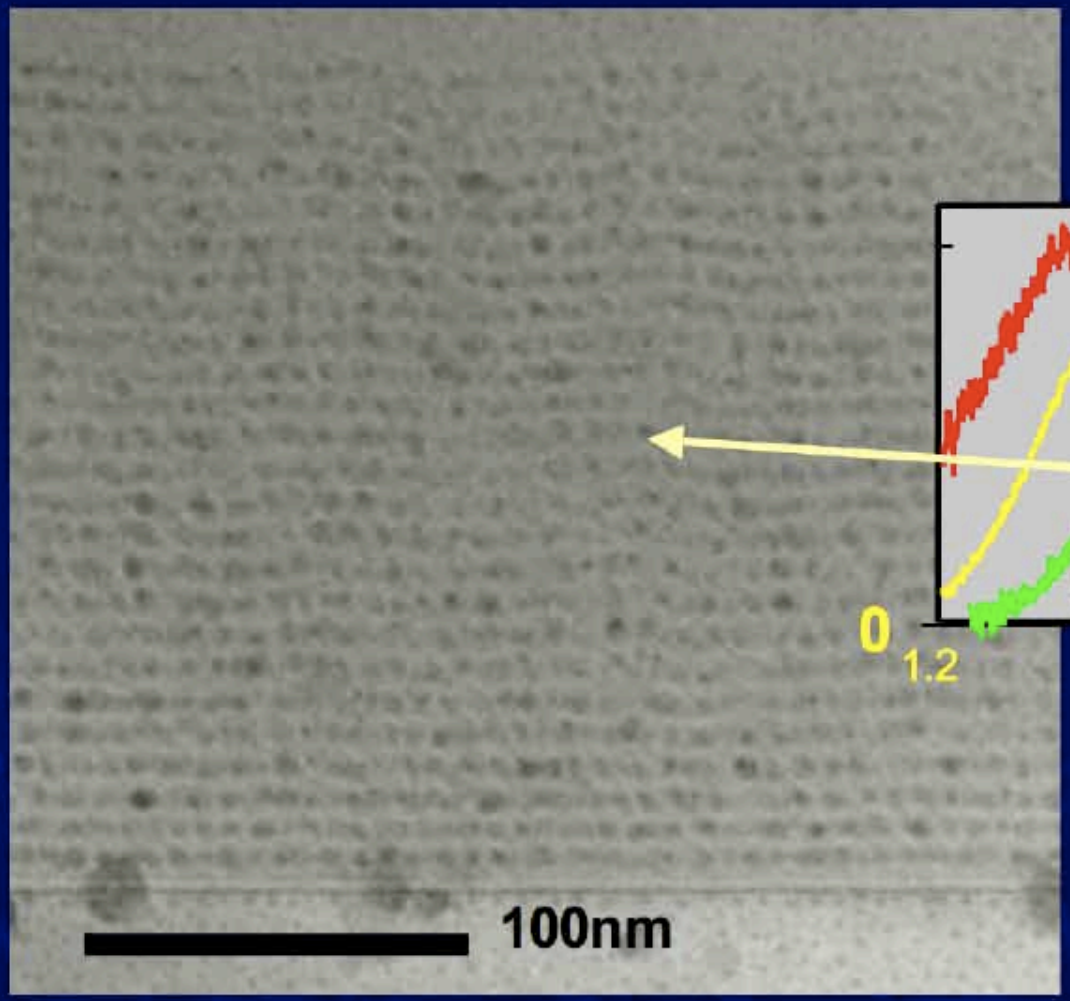
. high-density contacts

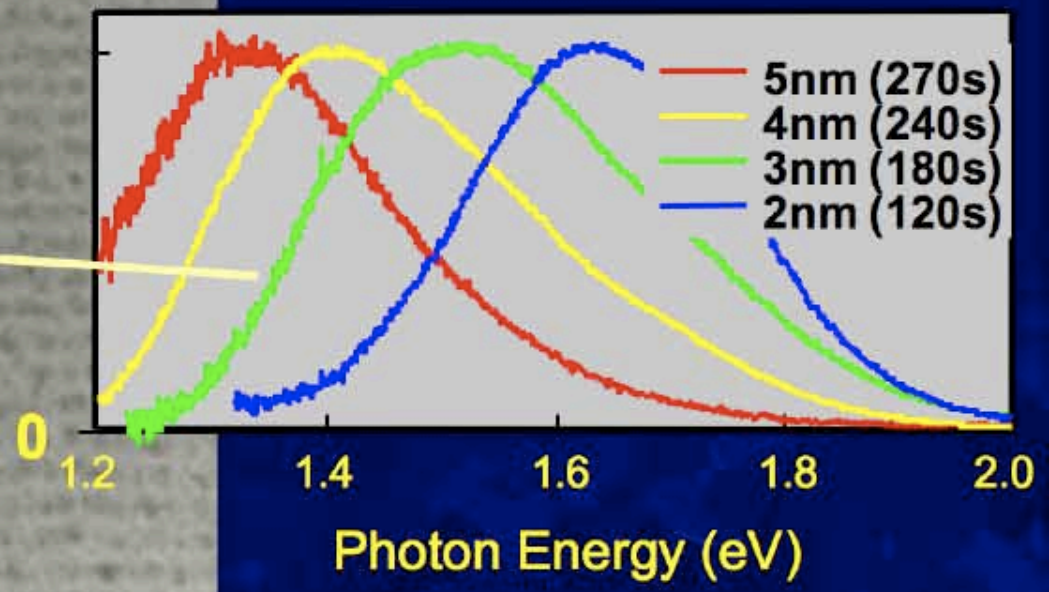
. good optics

. deposit then process

• excellent structure for innovation value-added *(multiple junction, quantum dot technology)*

Si quantum dot photoluminescence





Nanomaterials and Nanostructures for Space Photovoltaics

Dr. Sheila G. Bailey

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Dr. Ryne P. Raffaelle

NanoPower Research Laboratories, Rochester Institute of Technology,

Dr. Stephanie L. Castro

Ohio Aerospace Institute, Brookpark, OH, 44135, USA.

Dr. Christopher Wronski

The Center for Thin Film Devices, Penn State

Dr. Alex Freundlich

Texas Center for Superconductivity and Advanced Materials, Univ. of Houston

Dr. Rosa Leon

Jet Propulsion Laboratory

TECHNICAL GOALS

- Identifying suitable nanomaterials (matching the bandgaps, electron affinities, and compatibility of the various PV materials to the desired properties) to determine a potential theoretical structure.

- Selecting a compatible structure commensurate with our capability to actually manufacture the dots (whether by deposition from a single source precursor. by laser ablation, or Stranski-Krastanow growth)

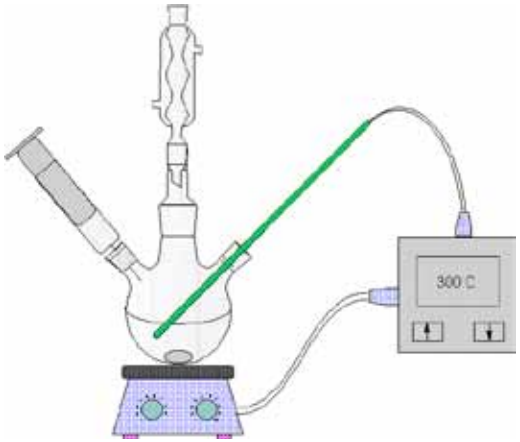
- Incorporate the dots into a p-i-n structure without inducing significant defects into the cell

- Characterize the resultant cell structure.

- The three solar cell material areas are:
    1. III-V multi-junction cells
    2. Amorphous silicon cells
    3. Polymer solar cells

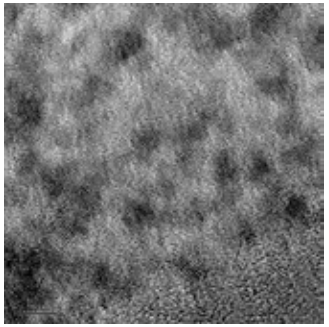
SYNTHESIS OF QUANTUM DOTS

Colloidal Synthesis

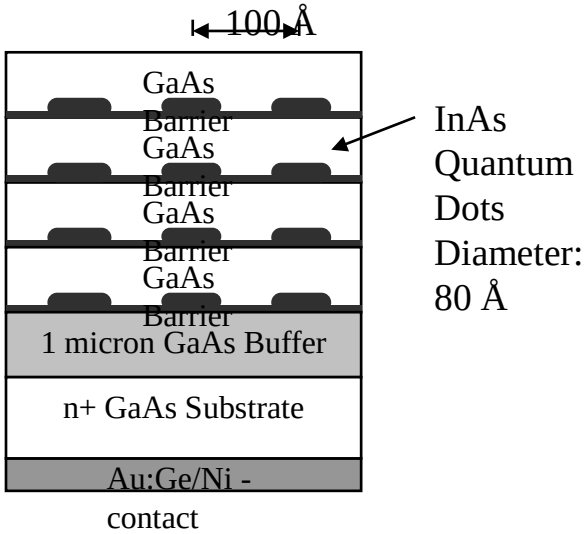


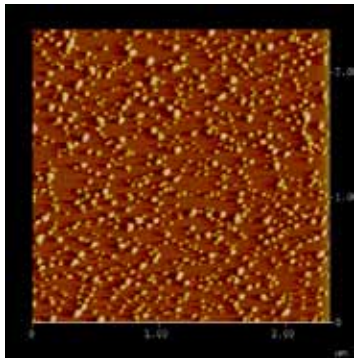
Colloidal CdSe QDs varying from 5-20 nm diameter

Colloidal $CuInS_2$ TEM (5 nm scale)

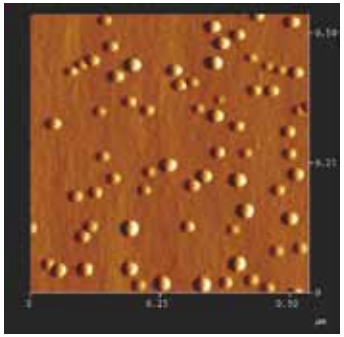


Stranski-Krastanow growth



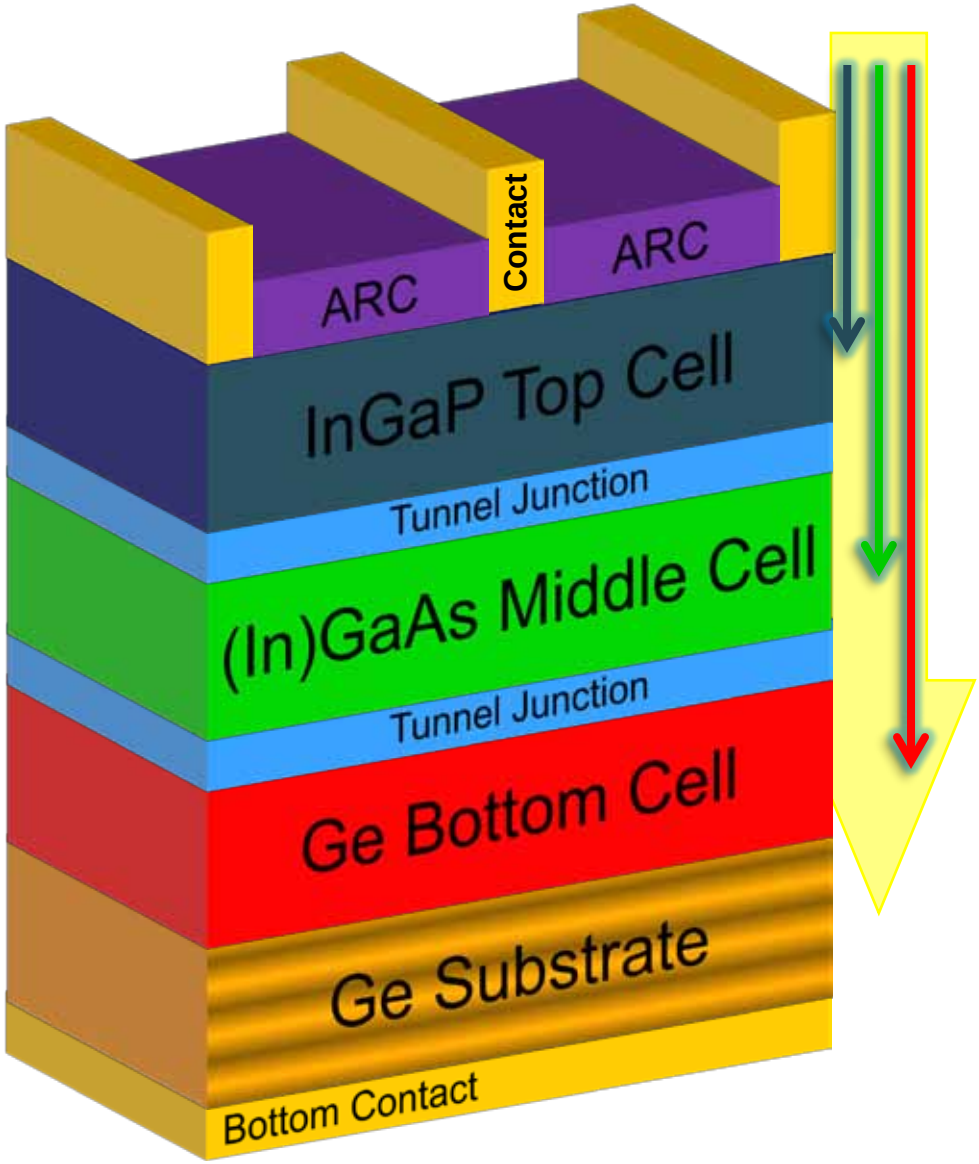


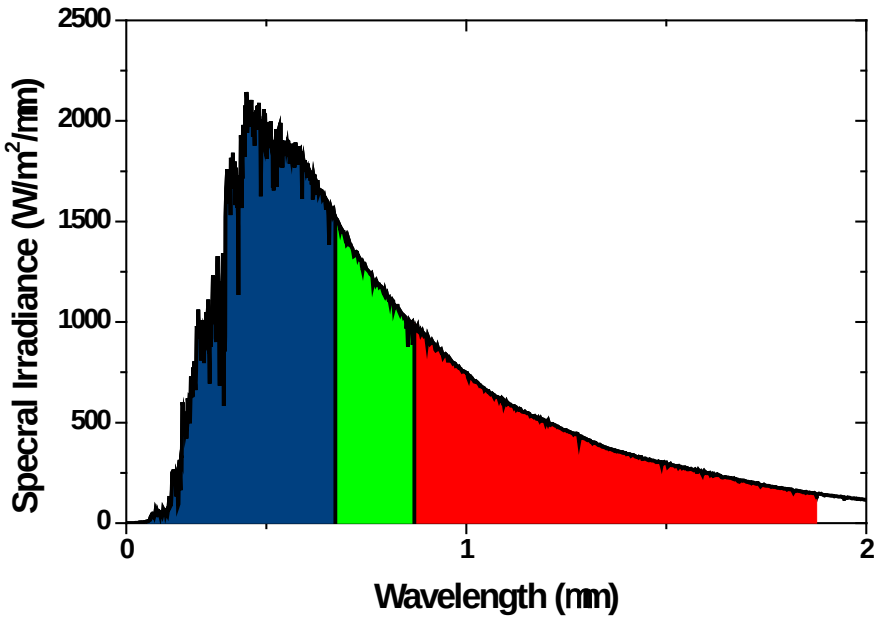
InAs QDs on GaAs



InAs QDs on InGaAs

State-of-the-Art III-V PV



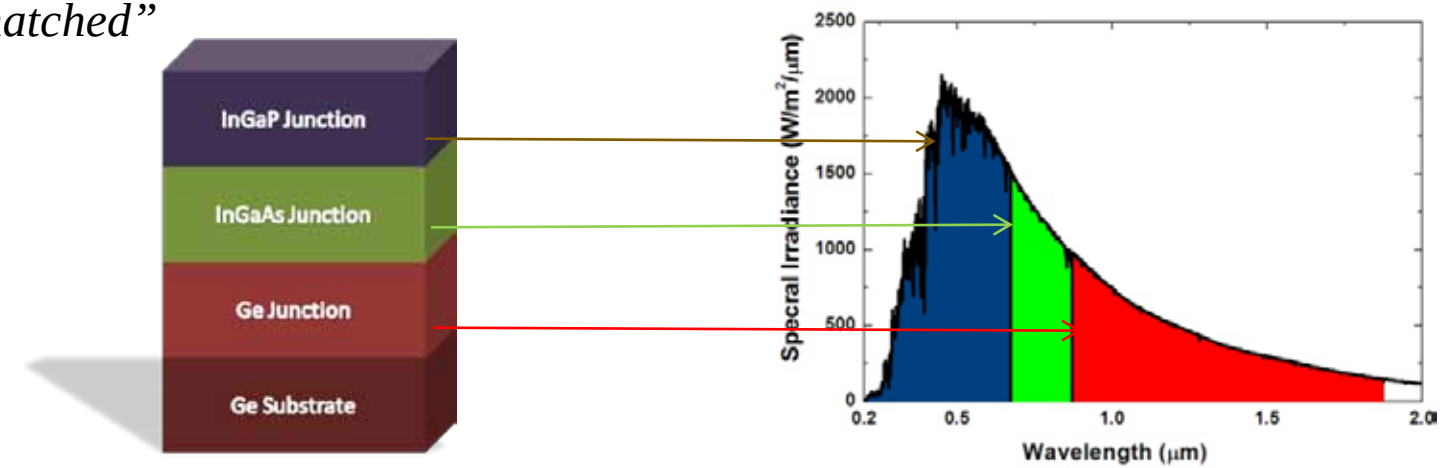


- Current SOA uses three junction in series
- Best cell efficiency ~31% (1 Sun) and 40% (250 Sun)
- Concentrator Module Efficiency ~30%

SOA Space Solar Cells

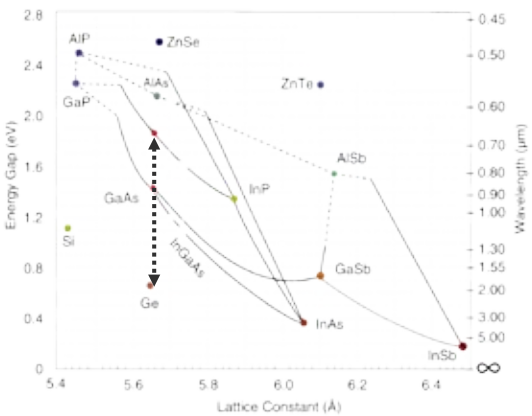
Lattice-Matched Triple Junction

Individual junctions must be "current-matched"



~33% Shockley-Queisser Limit

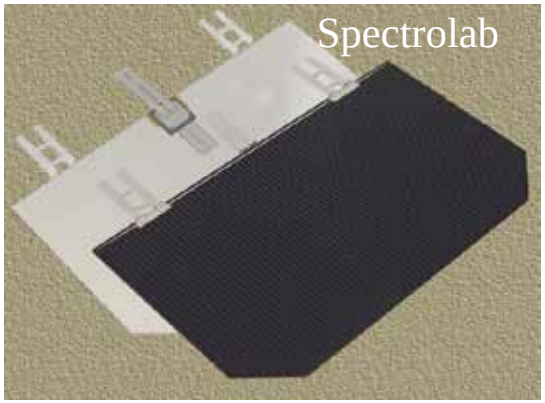
These cells, the ZTJ for Emcore and the XTJ for Spectrolab, are currently undergoing AIAA S-111 testing and are part of a mantech program for the U.S. government. Lot averages are ~30% efficient under 1 Sun AM0.

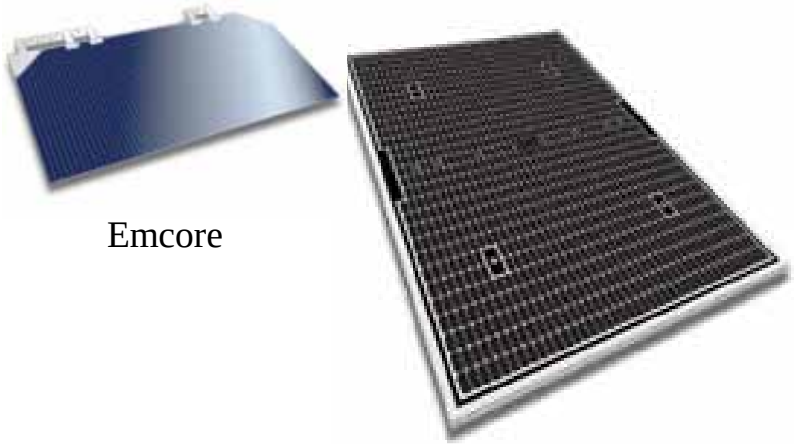


Higher Efficiency Approaches

- Metamorphic Growth
- Inverted Metamorphic Growth
- 4, 5, … Junction Devices
- Dilute Nitride Devices
- Mechanical Stacking
- Optical Spectrum Splitting
- Concentrator Designs
- Quantum Confinement

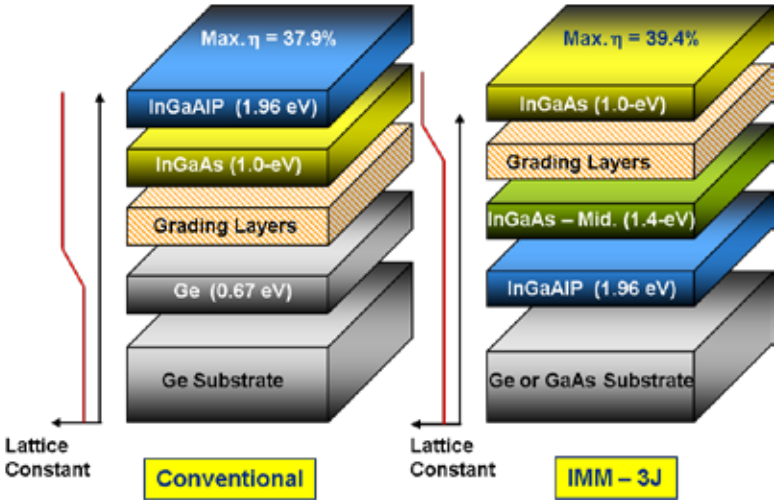
(Quantum Wells, Wires, and Dots)

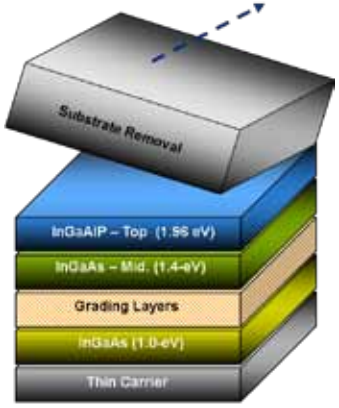




Efficiency from 30% to 40% and beyond?

Ultra High Specific Power Solar Cells - IMM ELO





Final IMM – 3J Structure

Courtesy Paul Sharps, Emcore Photovoltaics

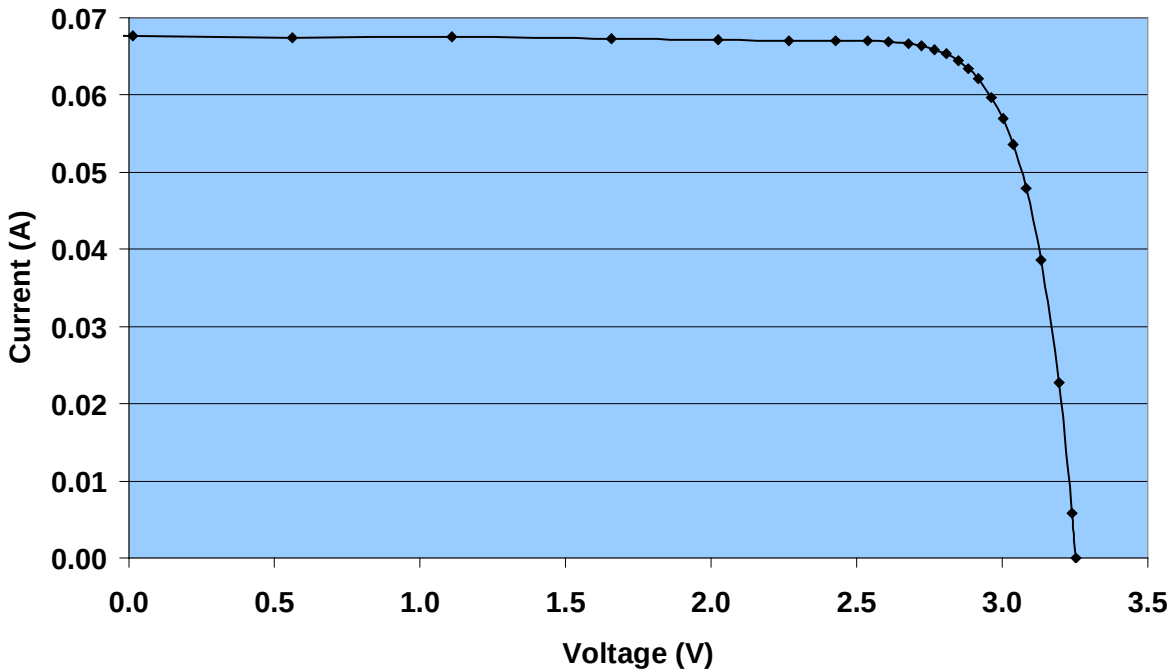
- IMM – Inverted MetaMorphic OMVPE Growth of multijuction cell – improved bandgap matching to solar spectrum – greater than 33% 1 sun AM1.0 efficiency

- ELO - Epitaxial Lift-Off – dramatic reduction in cell mass by eliminating substrate mass and potentially improved durability and flexibility

At 33% efficiency, bare cell specific power values > 3,000 W/Kg & > 440 W/m2

IMM Mulitjunction Solar Cells

Junctions	Bandgaps (ev)	Theoretical Efficiency	J_{sc} (mA/cm^2)
3	1.9/1.33/0.92	38.8	20.2
4	2.0/1.46/1.08/0.77	41.8	17.5
5	2.13/1.64/1.28/1.0/0.75	43.9	14.2
6	2.22/1.76/1.42/1.15/0.92/0.7145.3	45.3	12.2

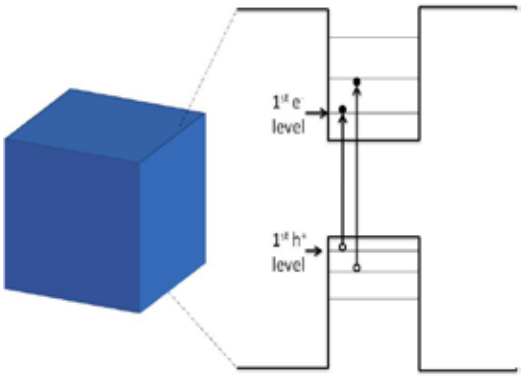


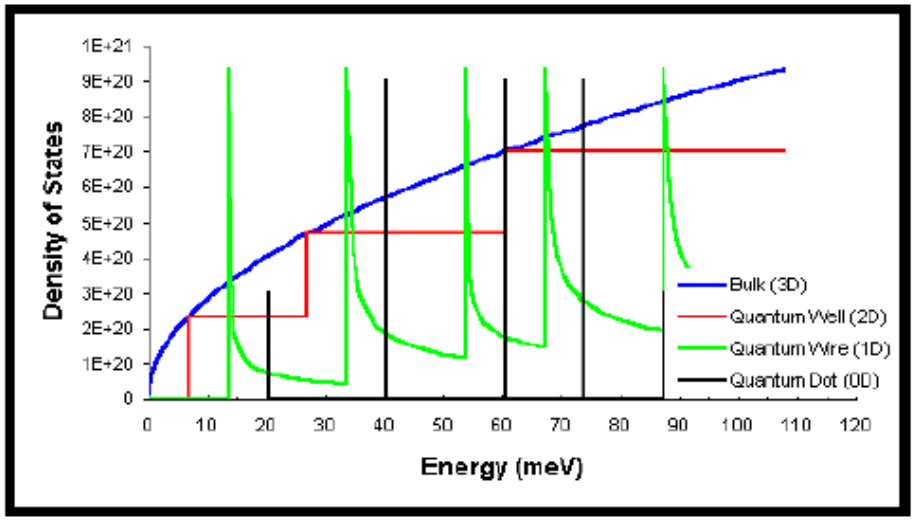
IMM 4 cm^2 Cell Under Coverglass Has Achieved 4J World Record 33.9%

Voc, mV	Jsc, mA/cm^2	FF, %	h, %
3255	16.91	83.3	33.9

Slide courtesy of Paul Sharps, emcore, Space Power Workshop 2009

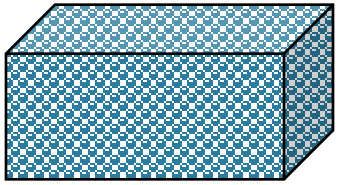
Quantum Confinement



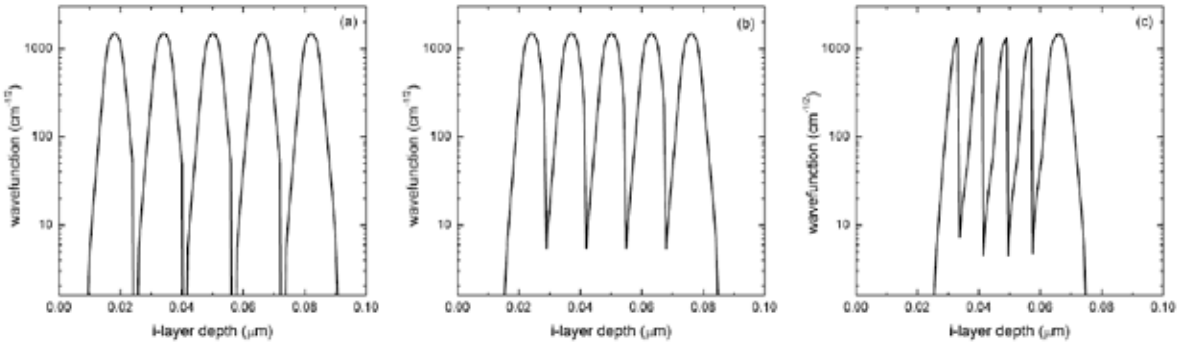


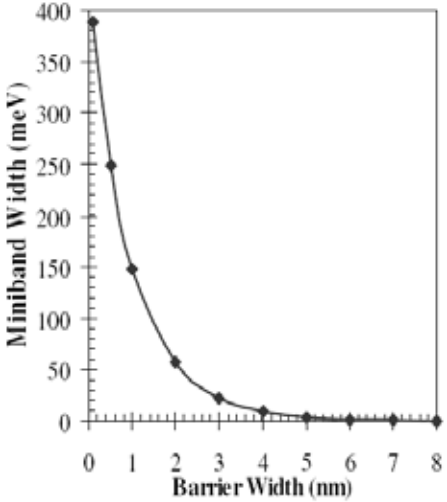
$$E_{x,y,z} = \frac{\hbar^2 \rho^2}{2m^*}\left(\frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2}\right)$$

- Discrete Density of States
- Size-based bandgap tuning

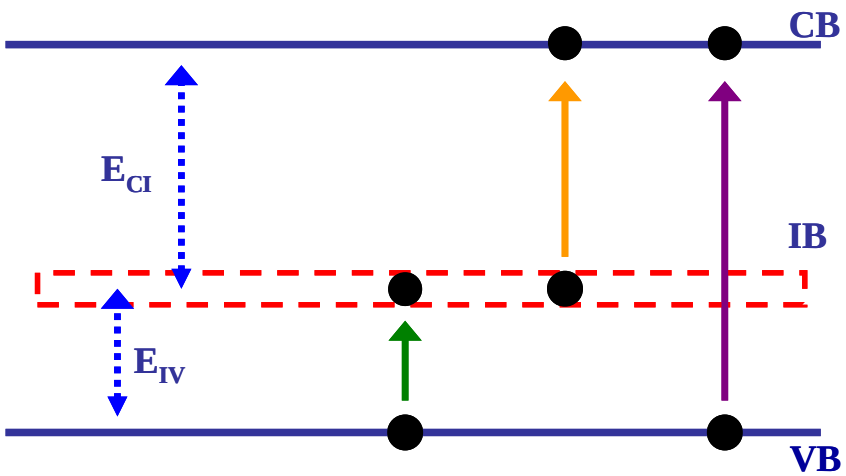


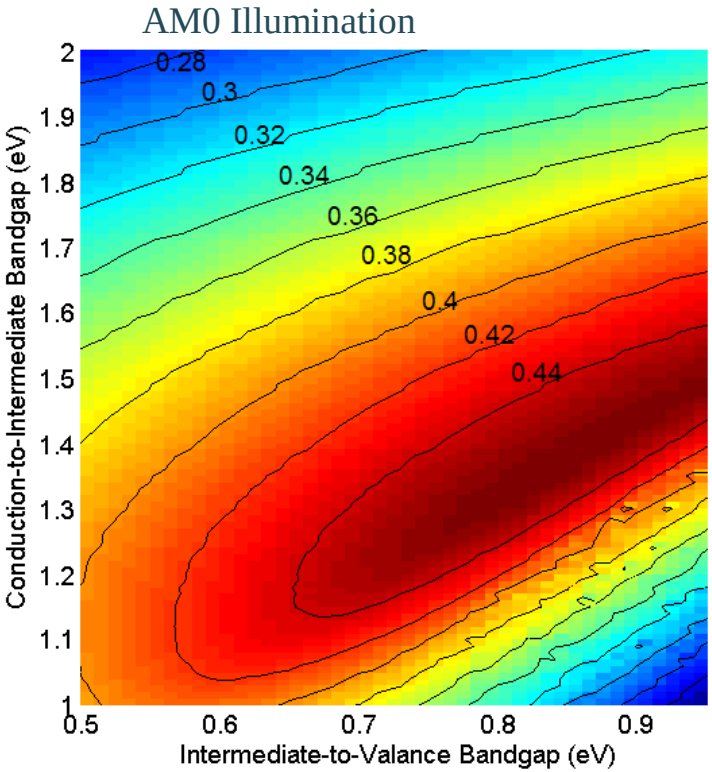
Silvaco ATLAS Modeling of QD Arrays:





Intermediate Band Solar Cell

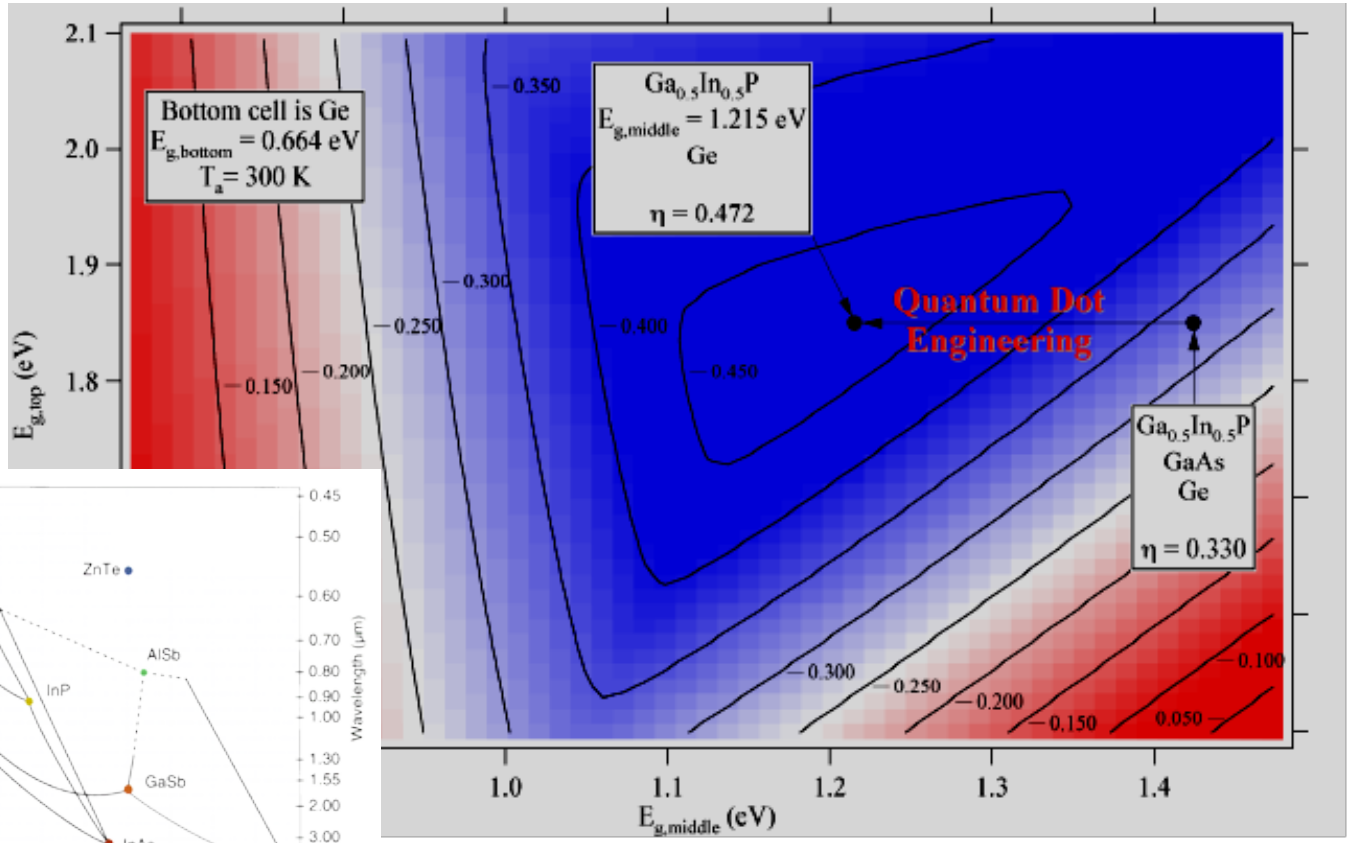


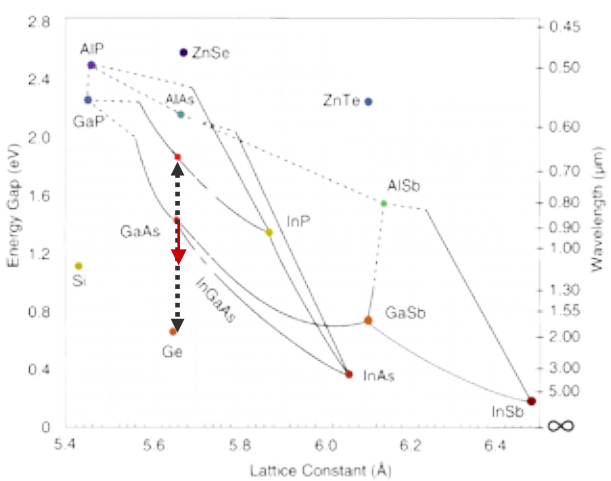


Spectrum	Maximum Efficiency	E_{CI}	E_{IV}
6000 K Blackbody	46.70%	1.49 eV	0.92 eV
AM0	45.80%	1.38 eV	0.85 eV
AM1.5G	49.40%	1.50 eV	0.93 eV
	48.60%	1.36 eV	0.75 eV

QD Spectral Tuning

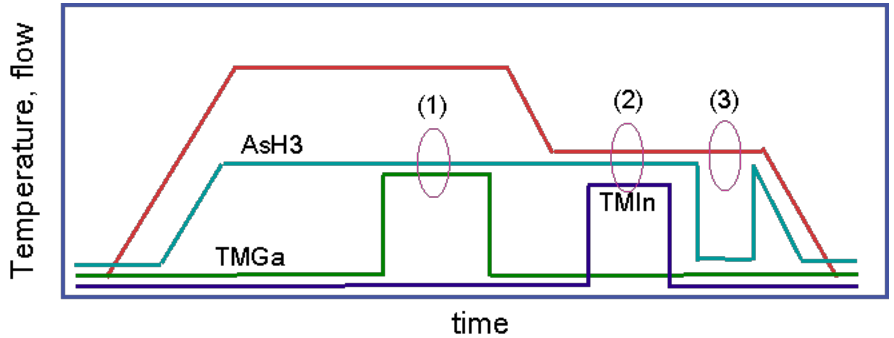
Detailed-balanced theoretical modeling studies have shown a potential increase from 33% to 47% with QD effective bandgap of middle cell of 1.2 eV in SOA lattice-matched TJSC

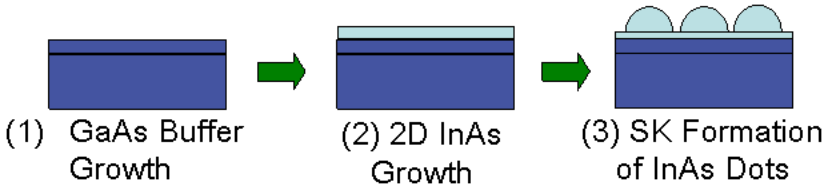


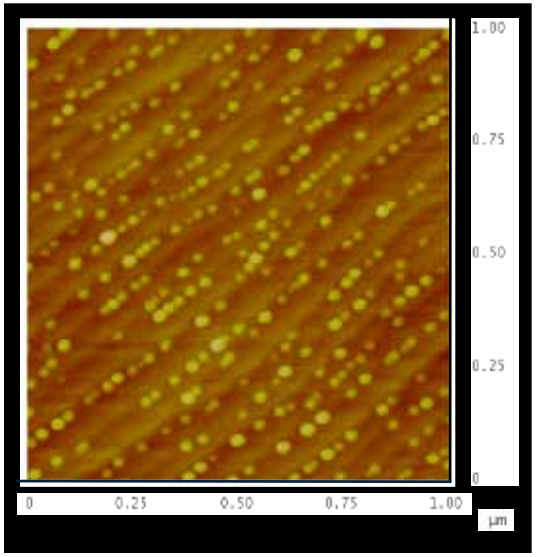


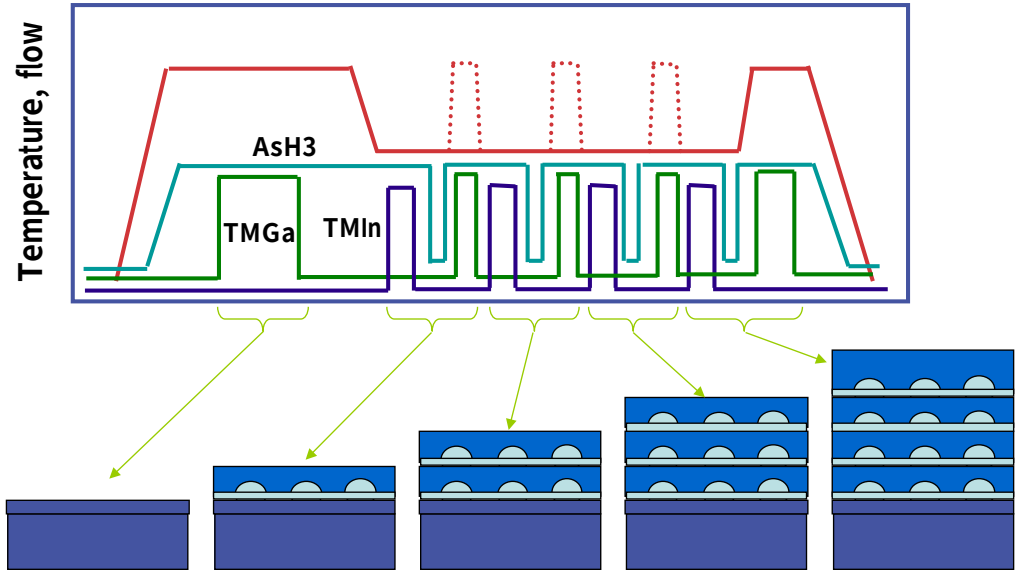
R.P. Raffaelle, D.M. Wilt, et. al., Proc. of the IEEE World Conference on Photovoltaic Energy Conversion **1**, 162-166 (2006).

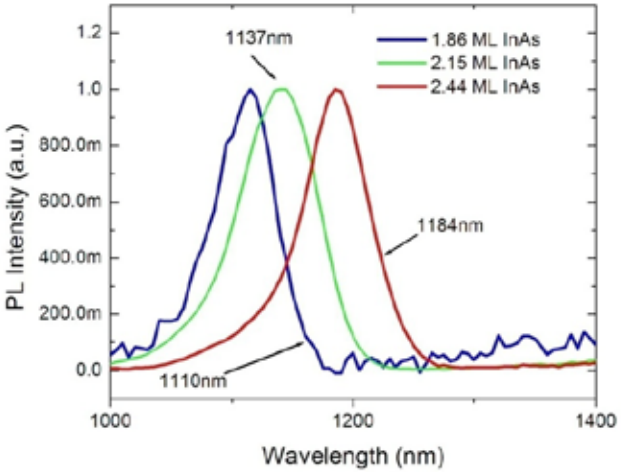
InAs QDs on GaAs



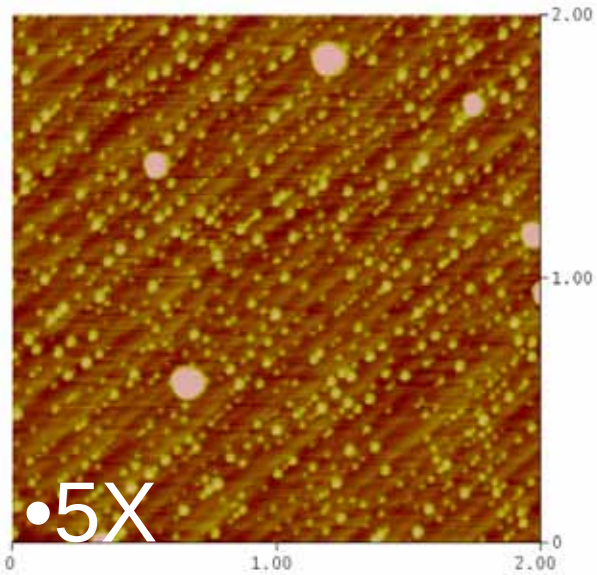




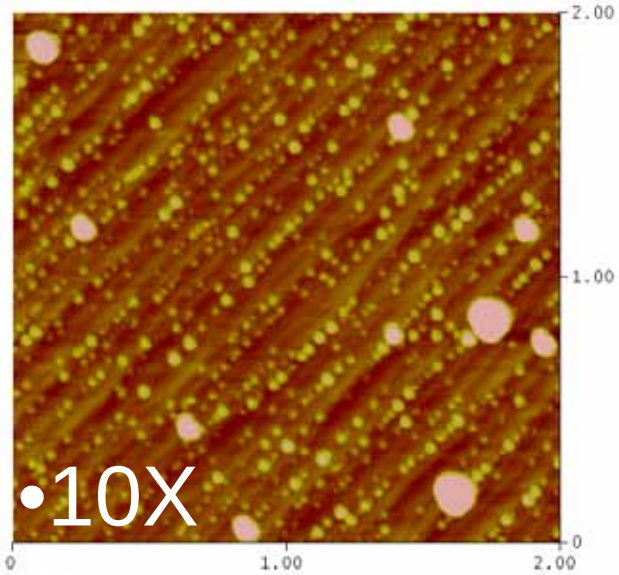




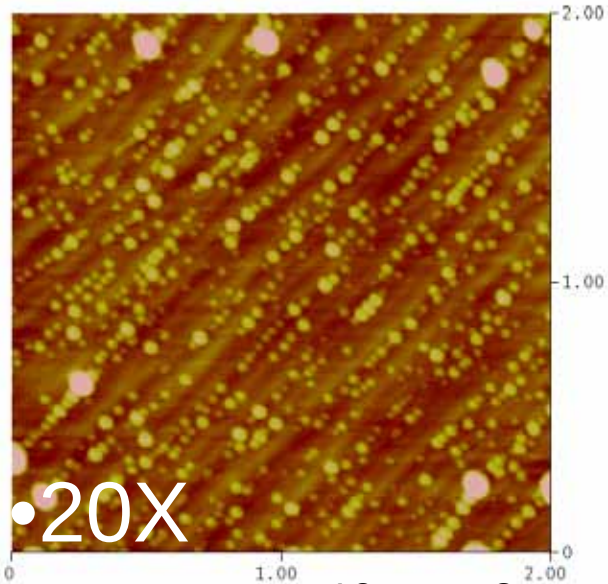
Increased InAs QD Stacks (Structures)



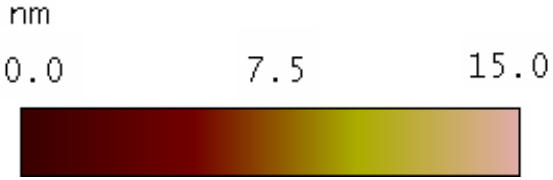
$r = 2.16 \times 10^{10}$ cm^{-2}



$r = 2.24 \times 10^{10}$ cm^{-2}

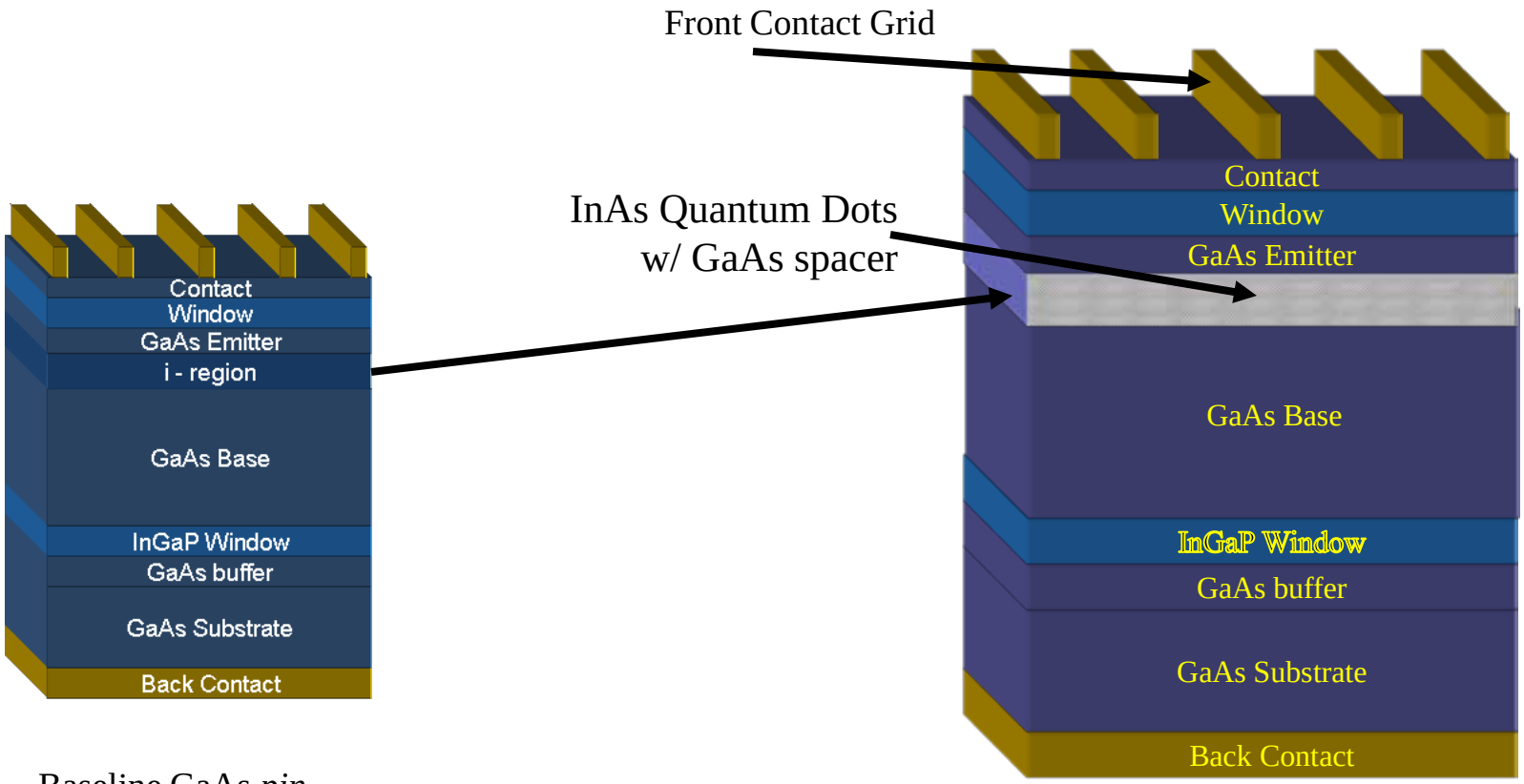


$r = 2.20 \times 10^{10}$ cm^{-2}



Stacked dots using strain compensation showed only slight density variation

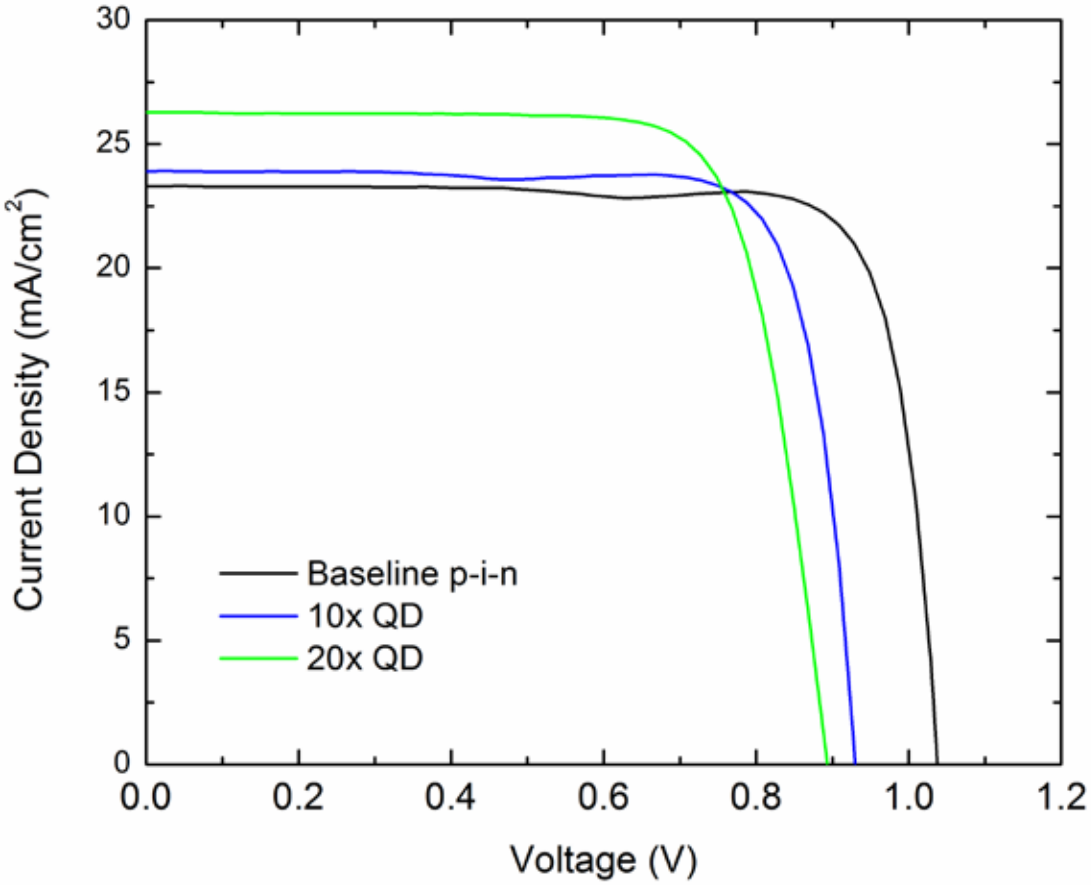
QD Cell Structure



Baseline GaAs *pin* structure

GaAs pin with InAs QDs

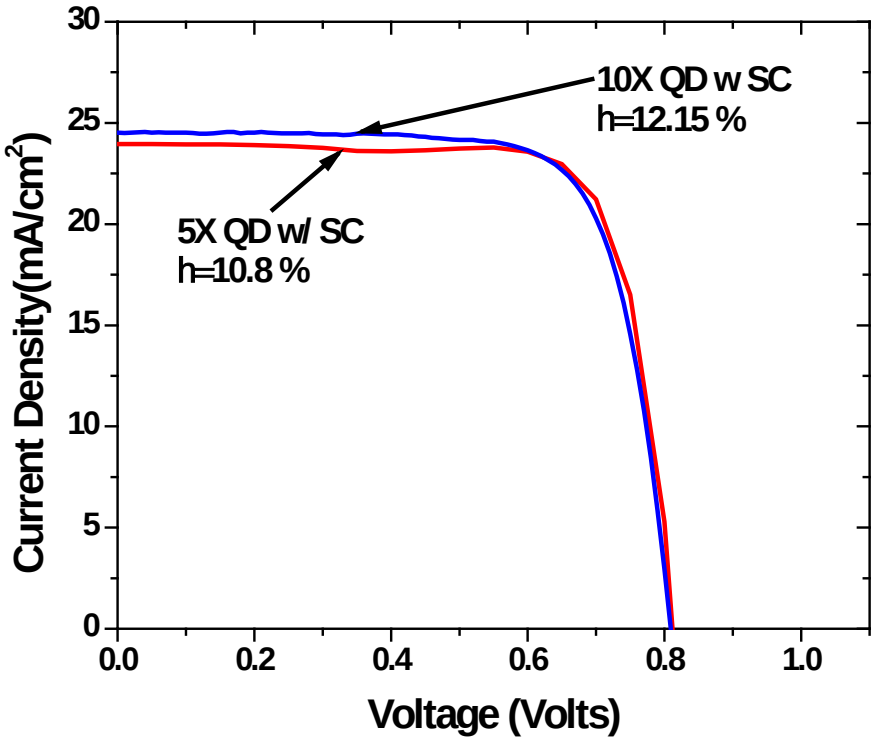
AM0 Photoresponse

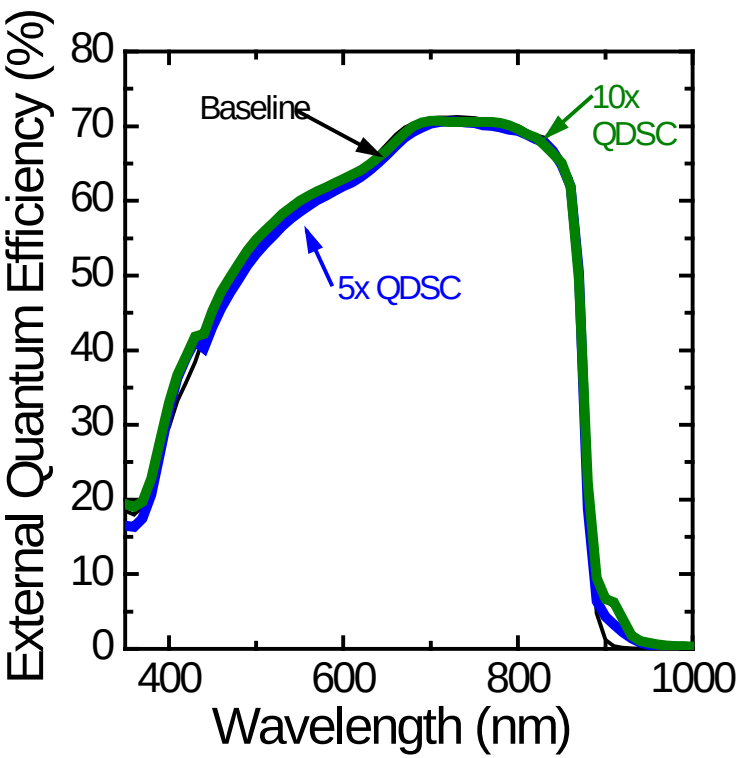


The 20x QD array yielded a 17% percent increase in J_{sc}

A potential h increase from 28.5% to 31%, if a similar J_{sc} increase and V_{oc} drop could be replicated in a conventional TJSC

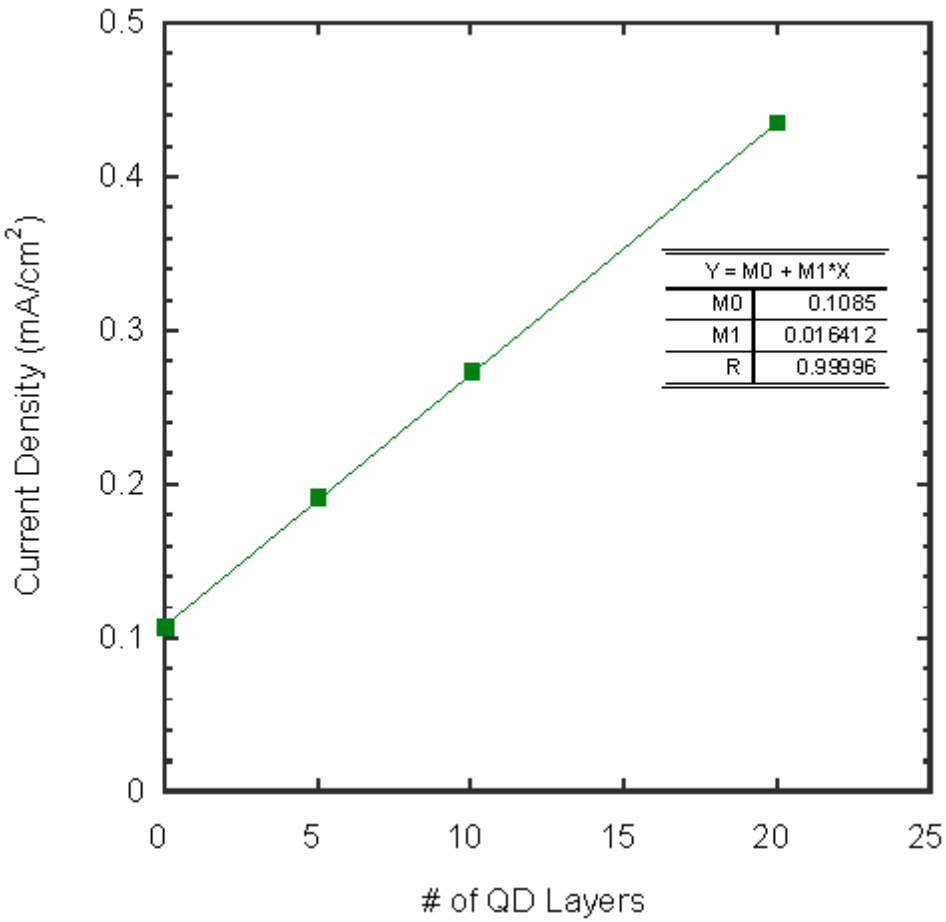
Increased Dot Stacking

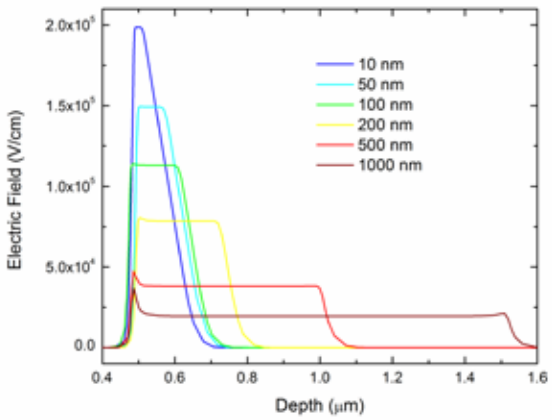




- Increased I_{SC} by addition of QD layers
  - **23.9 mA (5X) *Y*24.7 mA (10X)**

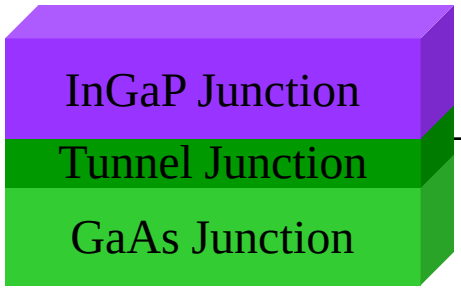
J_{sc}(>880nm) vs. #QD Layers

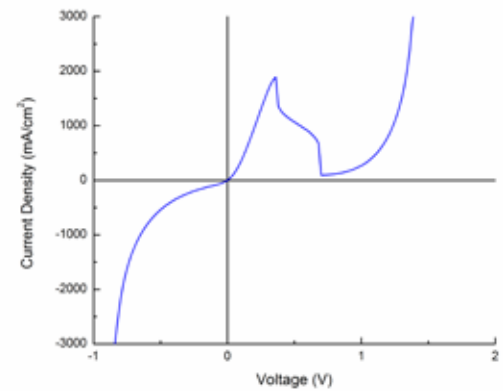


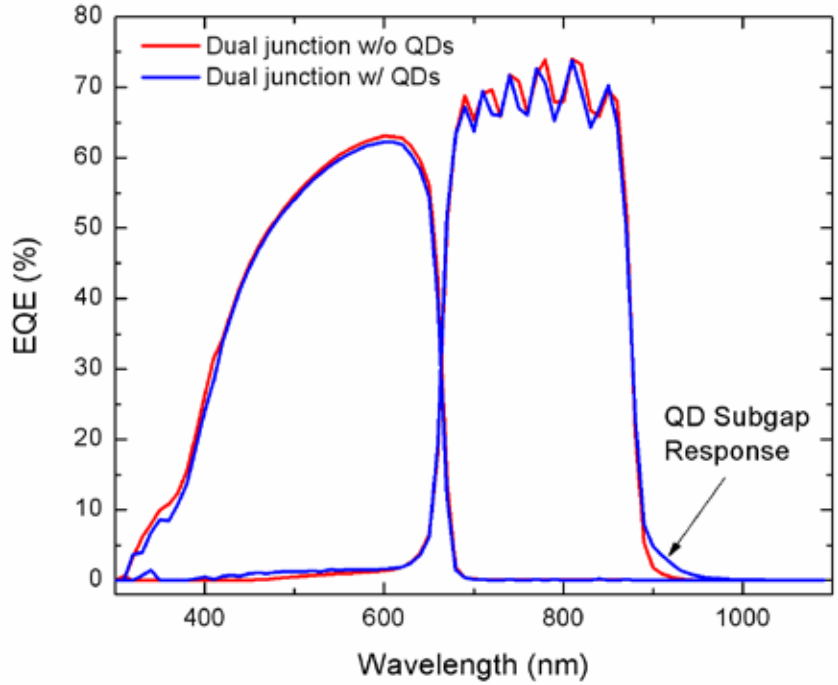


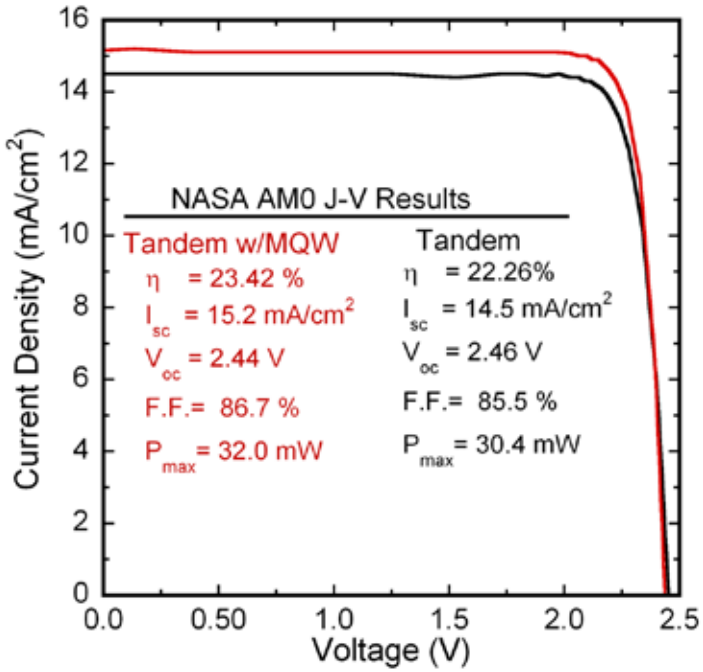
PC-1D simulation suggests a sufficient E-field exists for an increase of up to 100 layers

InGaP on GaAs Tandems

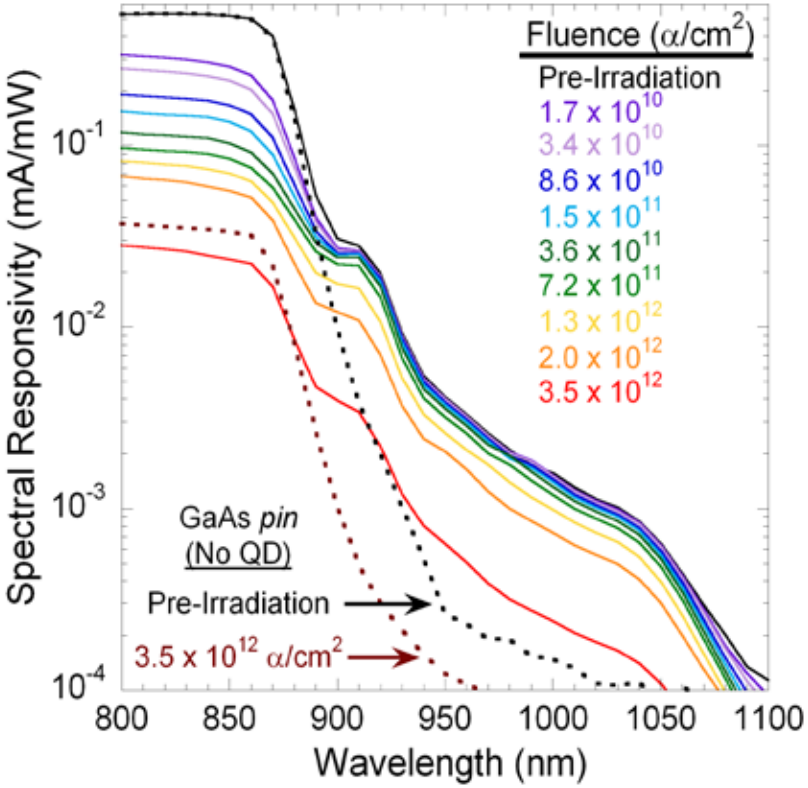


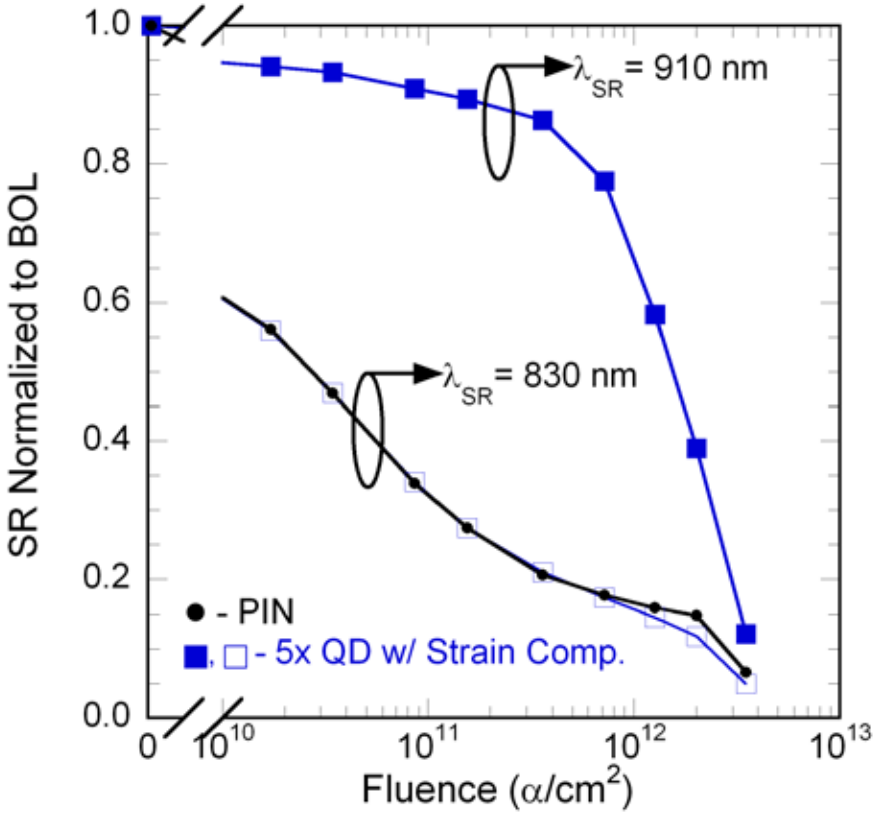




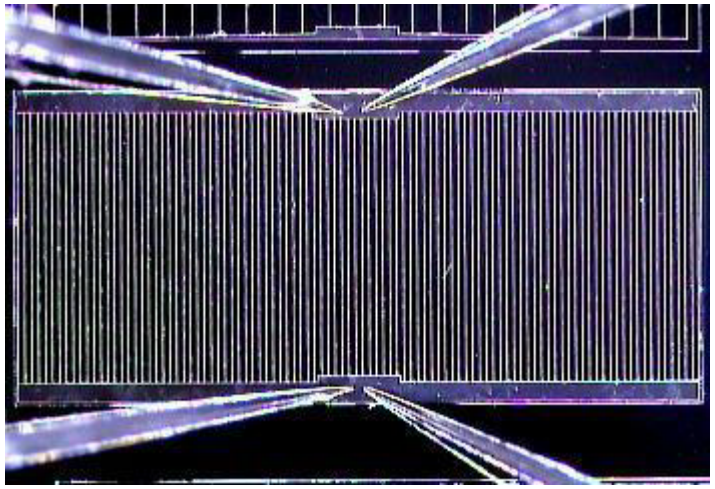


Radiation Tolerance (5x)

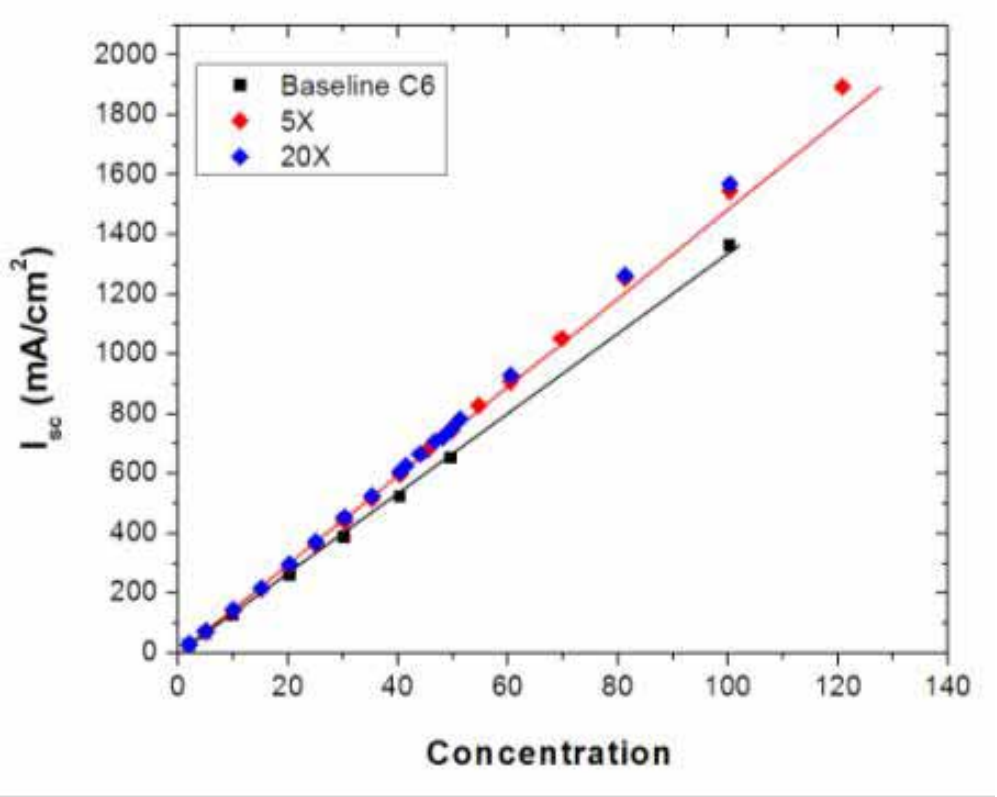




Concentrating Solar Cells



120X AM1.5 Concentration



QD Cells 14 % Efficiency Improvement over Baseline at 100 Suns

Conclusions

• ISS is Solar Array is now complete! Largest solar array ever deployed in space.

• IMM offers a new breakthrough in potential space photovoltaics performance

• Epitaxial lift-off offers a potential new paradigm in high specific power arrays.

• Thin films may also offer high specific power arrays with significant cost advantages.

• Nanostructured materials and device designs may offer new opportunties to continue to push the state of the art in space photovoltaic paerformance.

Acknowledgements

• David Wilt
• CFRDC Inc.

The US Government

Technololgy Investment Pathways

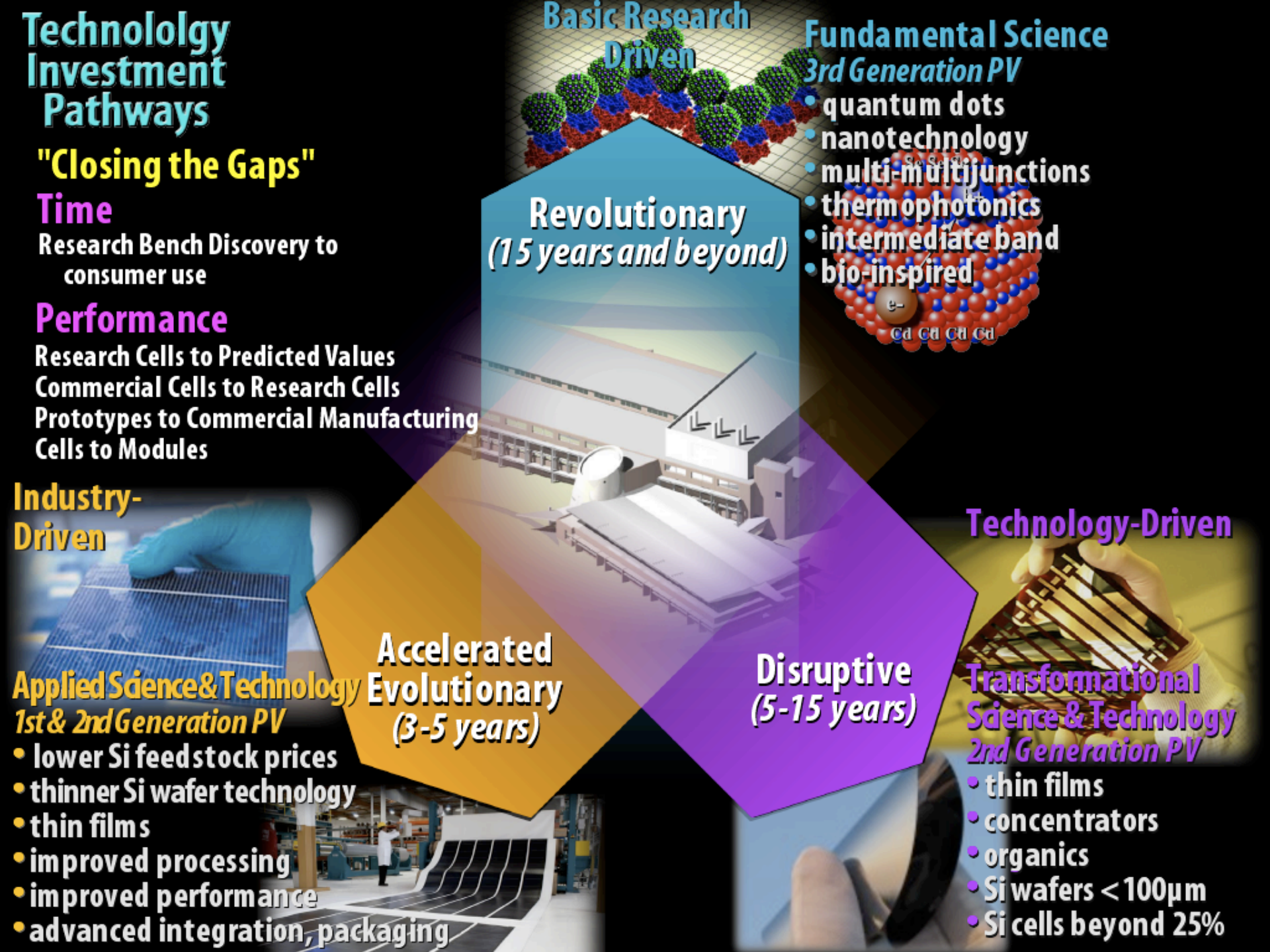
"Closing the Gaps"

Time

Research Bench Discovery to consumer use

Performance

Research Cells to Predicted Values
Commercial Cells to Research Cells
Prototypes to Commercial Manufacturing
Cells to Modules



Process Integration and Its Vision

Purpose: Optimizing device performance through understanding every aspect to the device (materials, interfaces) and the processes used

Integration of growth, characterization, and processing tools

- Flexible and robust
- Standardized transfer interface
- Size
- Controlled sample ambient within and between tools
- Allows for the development and/or incorporation of new processing/processes

Benefits

- Improved collaborations (industry/research orgs/universities)
- Provides answers to previously inaccessible or complex research/production questions
- Control and characterize critical surfaces and interfaces (impace n subsequent layers)
- Assesses process-related source chemistry, surface kinetics, and bulk reconstruction
- Controlled growth of layers and ability to alter interfaces
- Develop new techniques, methodologies, device structures, materials, and tools (growth, processing, and analytical)

The PV Manufacturing Challenges
(The "A-Team" Looking to the Future)

- **Automation**
- **Accessibility**
- **Anticipation**

  Technology Roadmap
  (Global, PV Industry-Wide, Equivalent to Semiconductor Industry, Predictive)

Efficiency!!! and Energy Use Changes

- Electricity Use Changes
- shift energy intensive work to sunny times (day time)
- maximize use of daylighting
- maximize use of passive solar
- smart appliances (run when power is available)
- smart homes (manage power distribution to lower overall use)
- smart grid
- “geothermal” space heating = increase electrical load

- Transportation Changes
- live closer to work
- electric cars
- electric (and extensive) public transit, *“street cars”*…
- save fossil fuels (bio-fuels) for flying, ships, and heavy equipment

"It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow."

Goddard

Proof:
1895 - Lord Kelvin "Heavier than air flying machines are impossible."
1897 - Lord Kelvin "Radio has no future."
1901 - Wilbur Wright "Man will not fly for fifty years."
1932 - Albert Einstein "There is not the slightest indication that nuclear energy will ever be obtainable. It would mean that the atom would have to be shattered at will."
1943 - Thomas Watson, Chairman of the Board of IBM, "I think there is a world market for about five computers."
1957 - Dr. Lee DeForest, Inventor of the Audion Tube, "Man will never reach the moon regardless of all future scientific advances."

What does it take to make a difference?
"Few will have the greatness to bend history itself, but each of us can work to change a small portion of events, and in the total of all these acts will be written the history of this generation."

Robert F. Kennedy