NREL National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

Solar Energy:
What's next for Solar Technology

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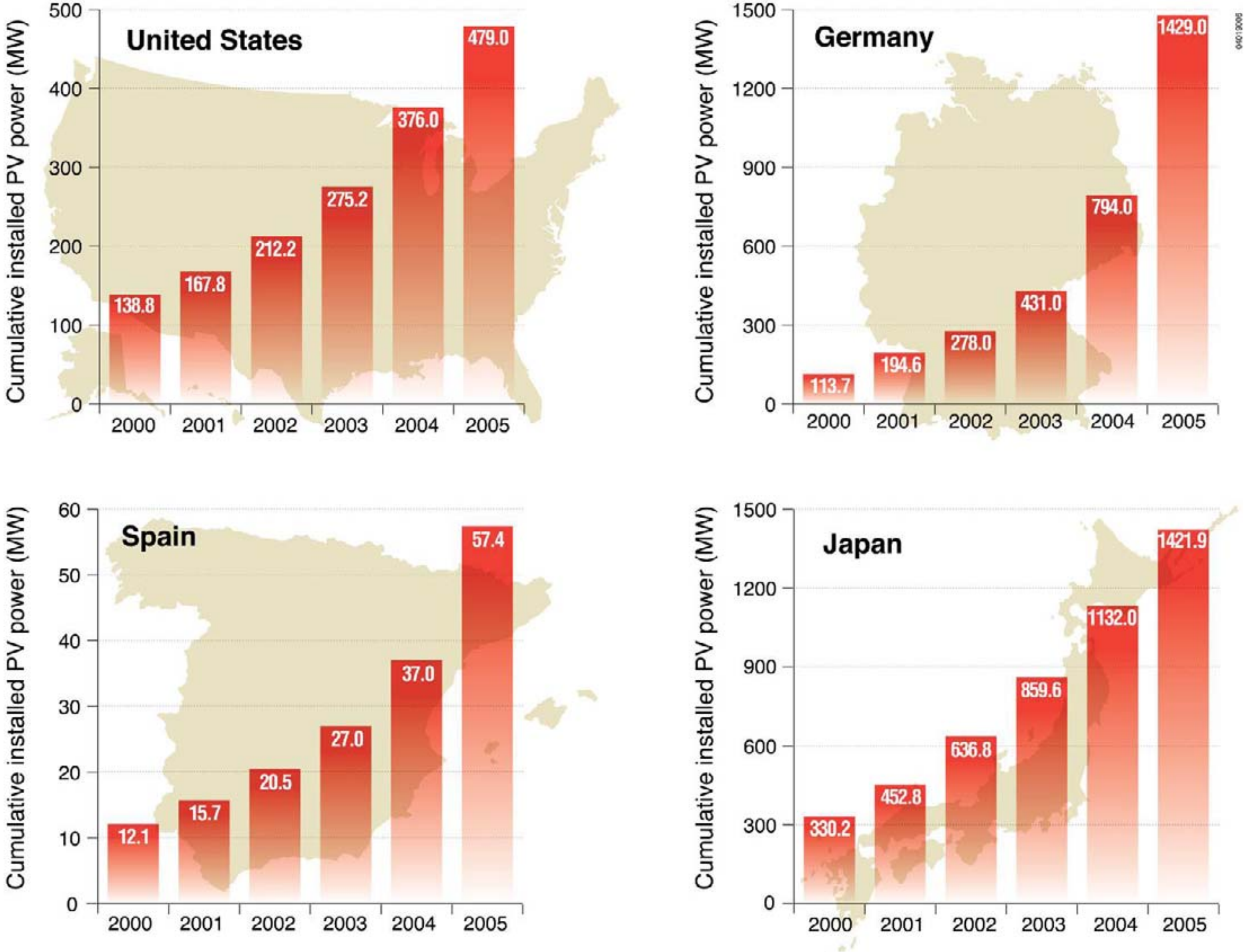
What’s next for Solar Technology?

- Market Growth
- DOE Programs
- Efficiency – Cost – Reliability
- NREL: Industry’s Partner
- Thin films
- Concentrators
- Silicon
- Technologies for future generations

PV has historically been a marginal power source, but incentives drove steep growth in demand from 2001-2005

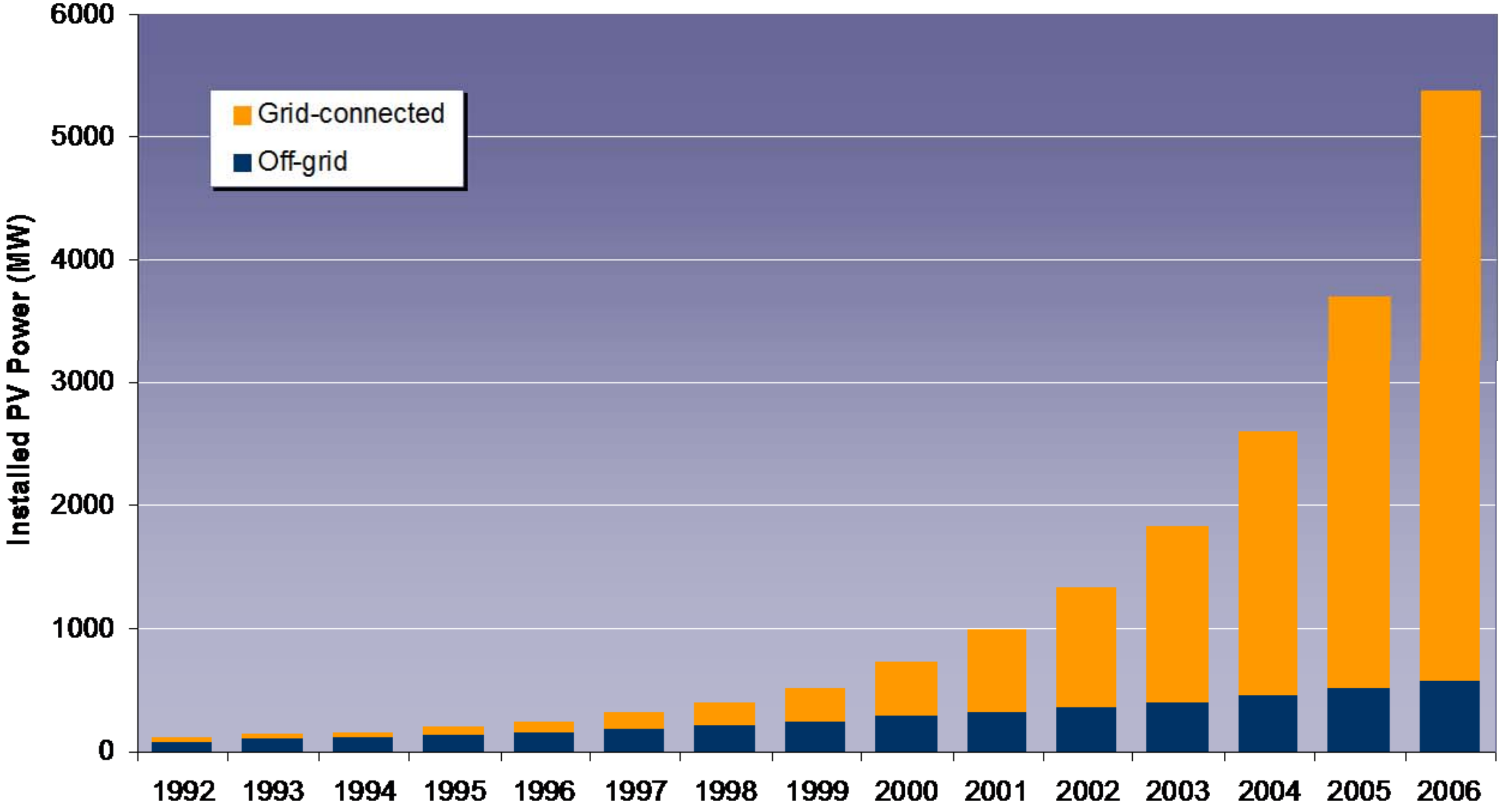


Source: International Energy Agency.

Incentive-driven demand is expanding production, but creating Si supply bottlenecks.

In 2006, installations totaled ~2GW, largely from grid-tied installations in Germany, Spain, Japan, and California

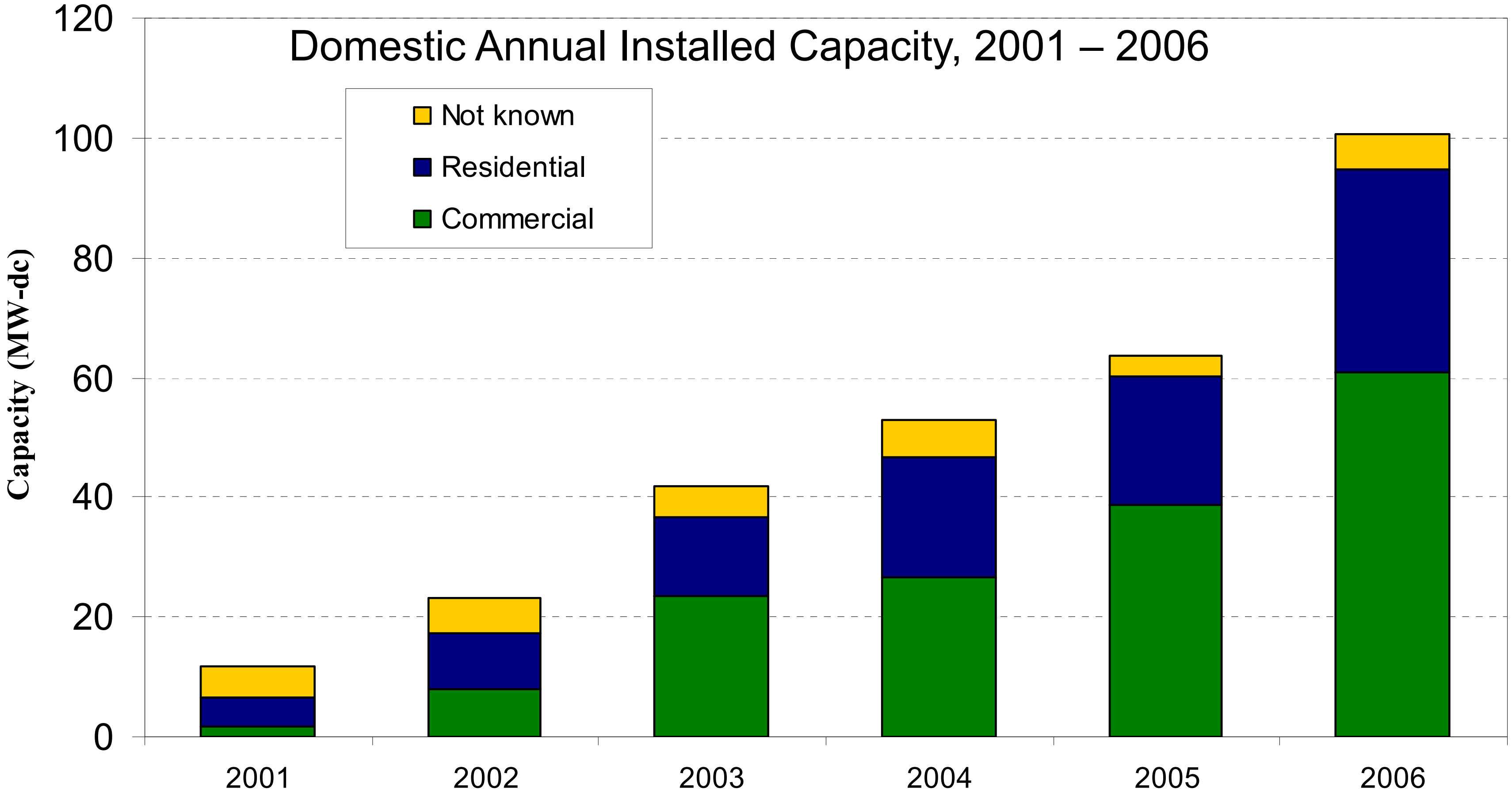
Cumulative installed grid-connected and off-grid PV power in the reporting countries – Years 1992-2006



Source: International Energy Agency.

Incentive-driven demand is expanding production, but creating Si supply bottlenecks.

In the past five years, installed PV capacity has grown both in the U.S. residential and commercial sectors

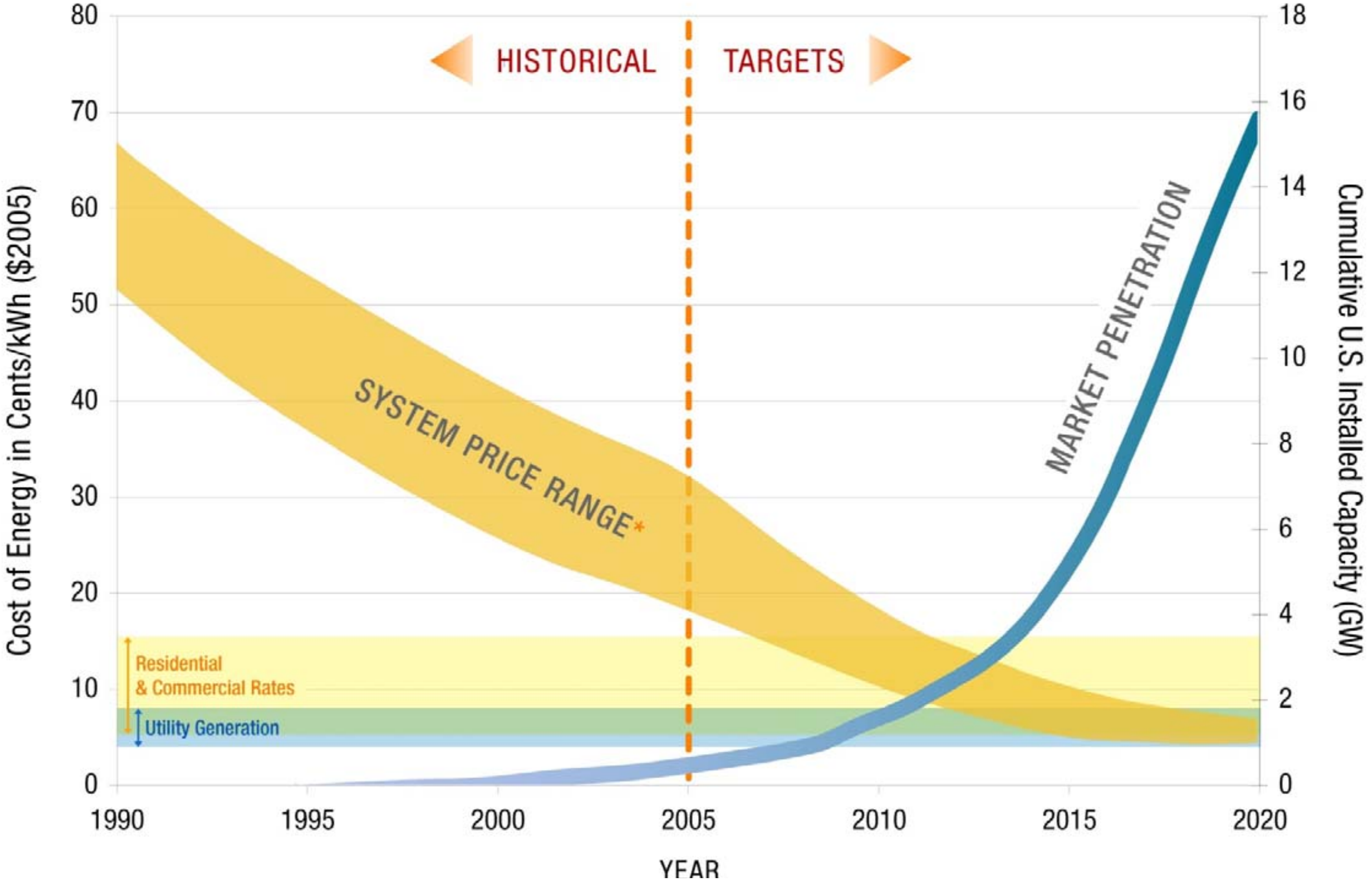

Domestic Annual Installed Capacity, 2001 – 2006

* Source: Prometheus Institute, 2007

In 2006, the commercial sector accounted for 60% of total installed capacity, up from 13.5% in 2001. Government incentives have driven this growth.

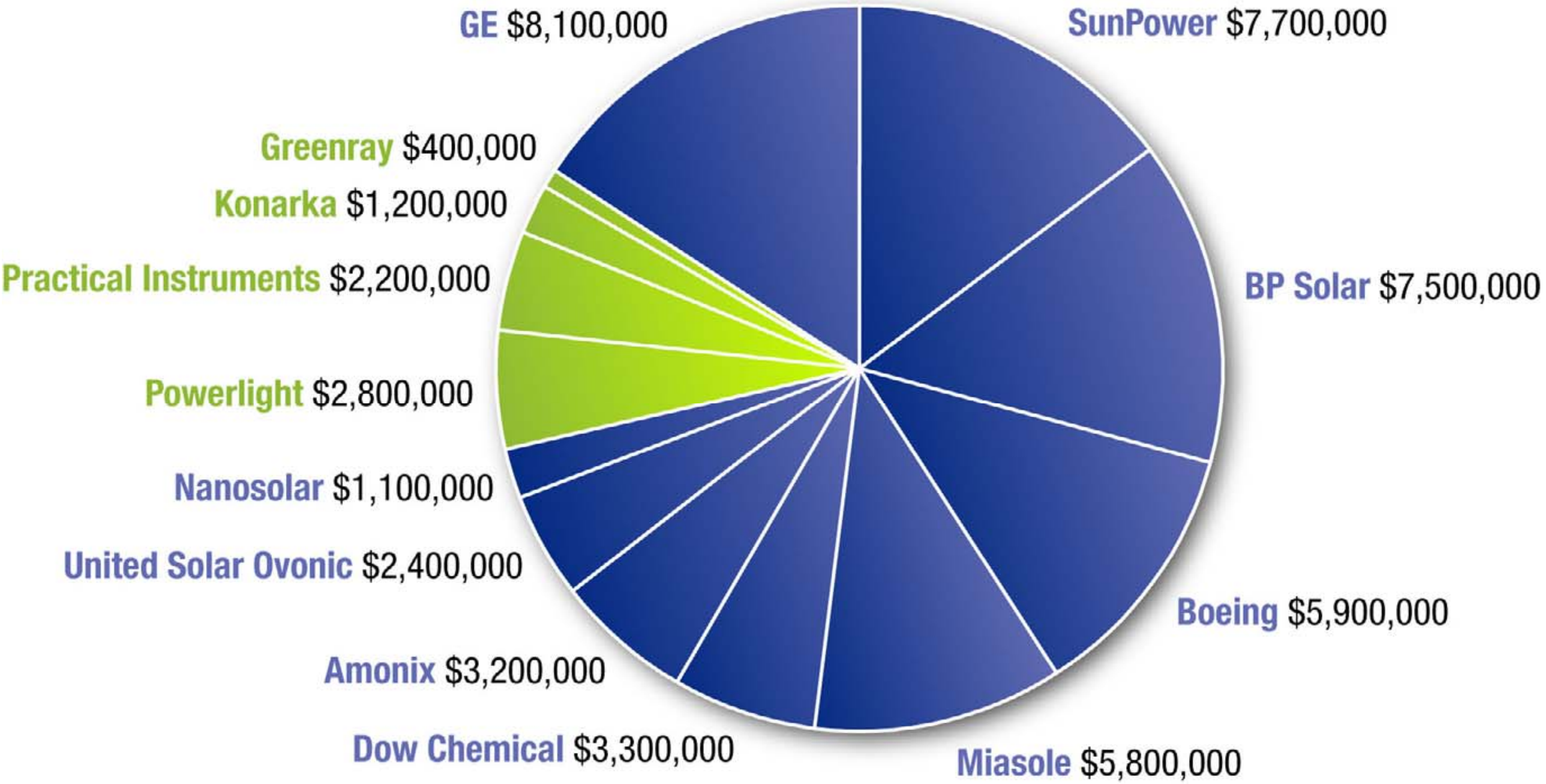
President's Goal for the Solar America Initiative (SAI)

Making Solar Cost-Competitive Nationwide 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

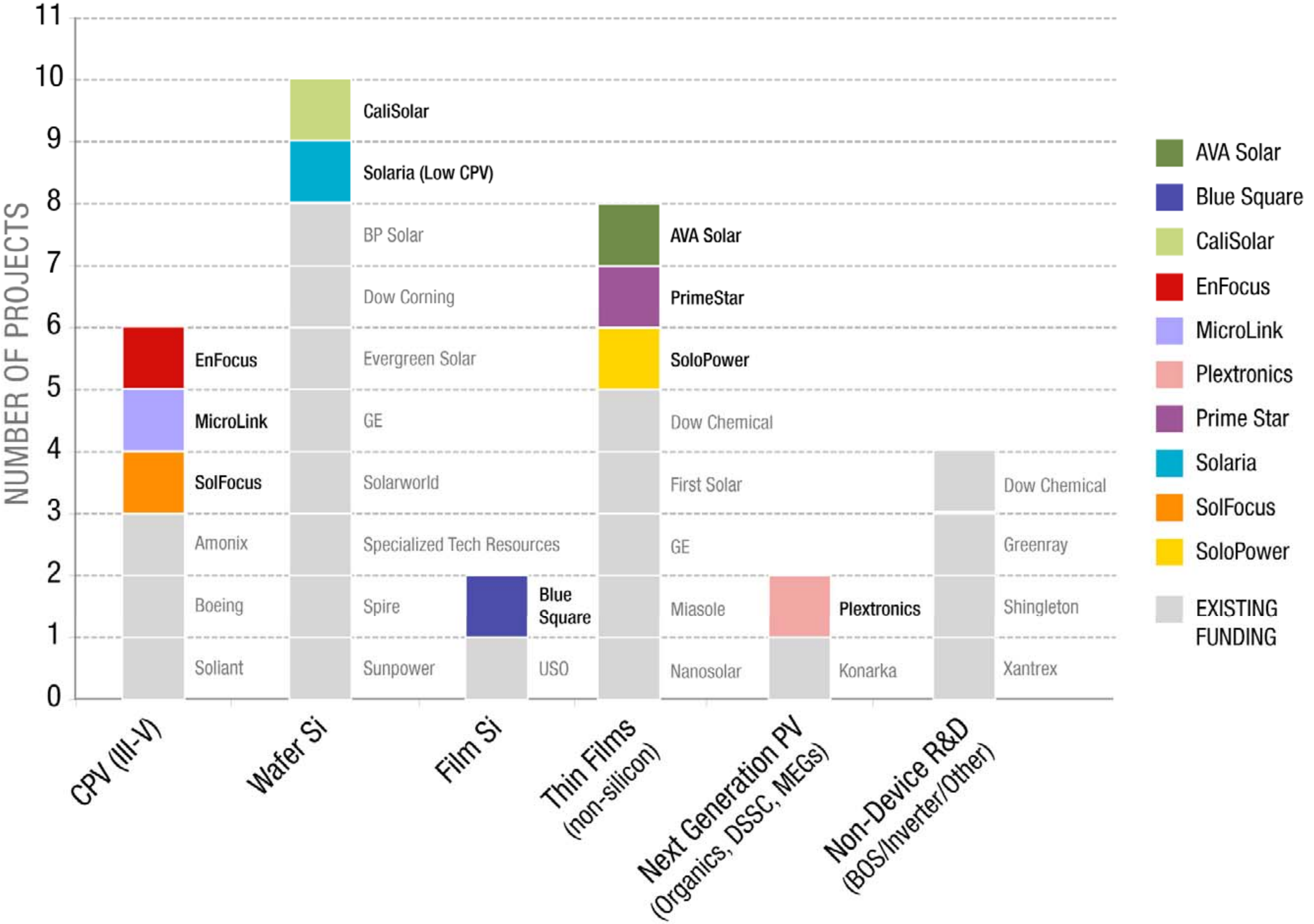
TPP Project DOE Funding Breakdown:
Year One Total Funding $51,600,000



Projects will include a broad cross-section of U.S. industry:

- Involving over 50 companies, 14 universities, 3 non-profits and 2 national laboratories in 20 states across the U.S. (subject to change)
- Teams will contribute well over 50% of the funding for these projects.

DOE’s Portfolio Balances Technology, Maturity & Risk



PrimeStar Solar: Production Scale-Up of World Record CdTe/CdS Cell

PrimeStar Solar

Technologies Addressed

CdTe Thin Film

Target Market

Utility and Commercial

Description

Develop commercial CdTe module production based on the NREL 16.5% world record CdTe laboratory solar cell technology. The increased module energy conversion efficiency will lower installation costs and open new markets for CdTe based thin film modules.

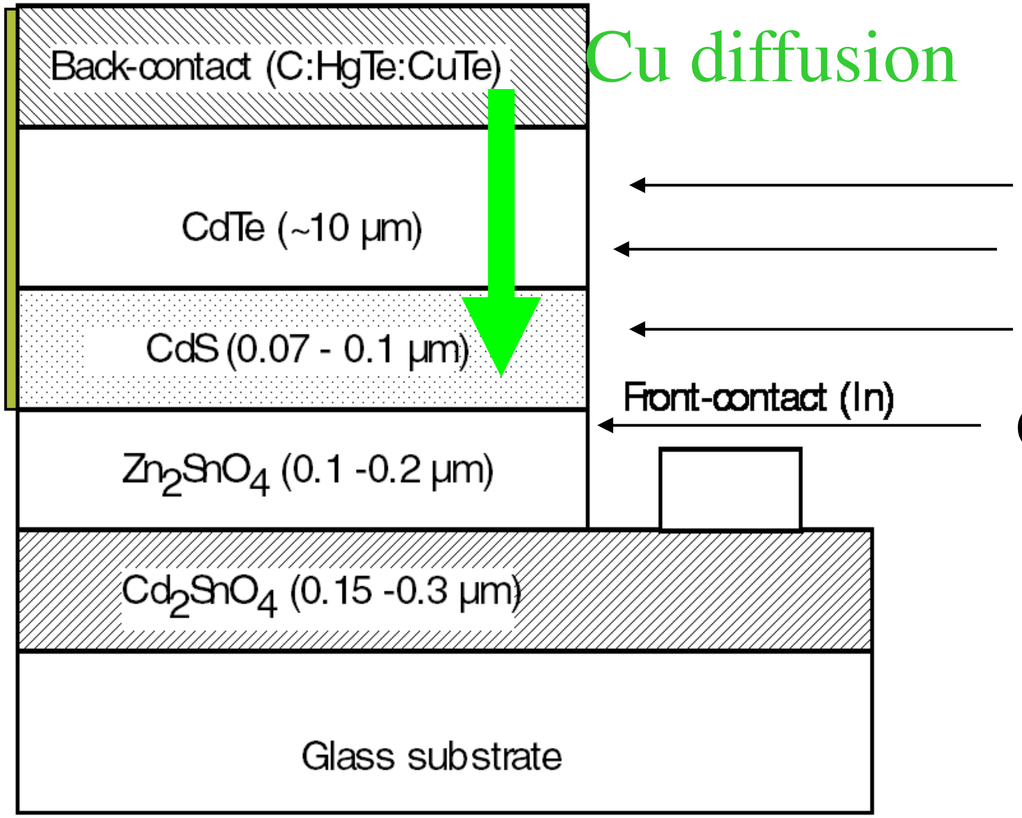
Resources ($)

Total Project	DOE Funds	Cost Share
$11,610,000	**$2,980,000**	**$8,630,000**

Annual Production (MW)

Baseline Production (2007)	**0 MW**
18 Month	**3 MW**
2010 Potential	**50 MW**

16.5% Efficient CdTe Solar Cells



Back-contact (C:HgTe:CuTe)

CdTe (~10 µm)

CdS (0.07 - 0.1 µm)

Zn_2SnO_4 (0.1 -0.2 µm)

Cd_2SnO_4 (0.15 -0.3 µm)

Glass substrate

Front-contact (In)

Cu diffusion

Anneal in $CdCl_2$

CdS_xTe_{1-x}

O content in CdS

CdS – ZTO interdiffuse

NREL – PrimeStar
Cooperative Research and Development Agreement

- PrimeStar negotiates a limited exclusive license to NREL's record efficiency CdTe solar cell structure and process
- Joint development of production scale processes to implement lab scale methods proven by NREL

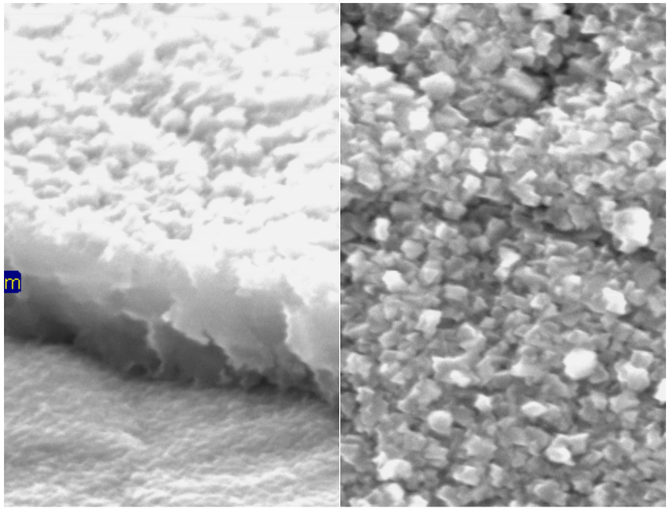
PrimeStar benefits

- **NREL experience**
- **Device fabrication from 1st stage absorber development**
- **Measurements**
- **Comparative performance assessment of multiple processes**

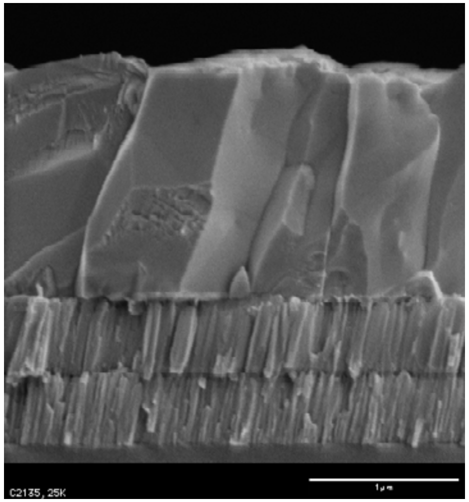
NREL benefits

- **First hand experience in scale-up**
- **Improved understanding of production process constraints**
- **Comparative performance assessment of multiple processes**
- **Baseline PDIL interactions**

CIGS *Thin Film Technology*

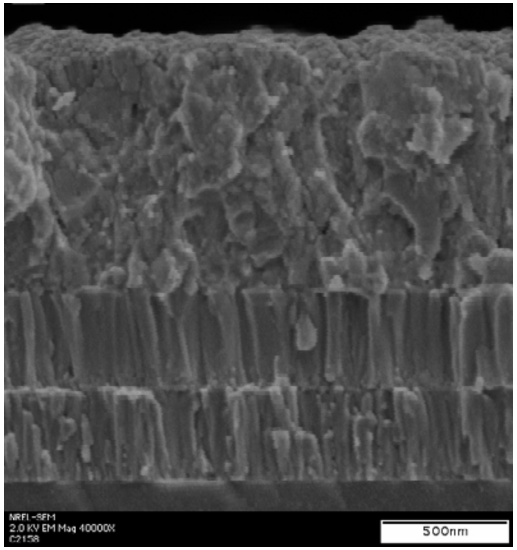


Industry 1.1μm in 5 min η 3-5%



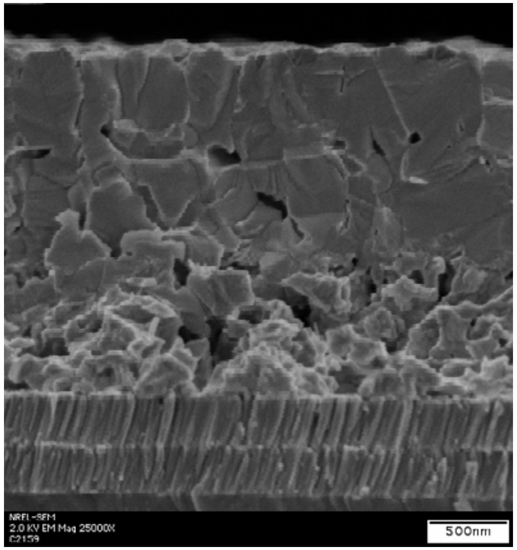
NREL

High Performance



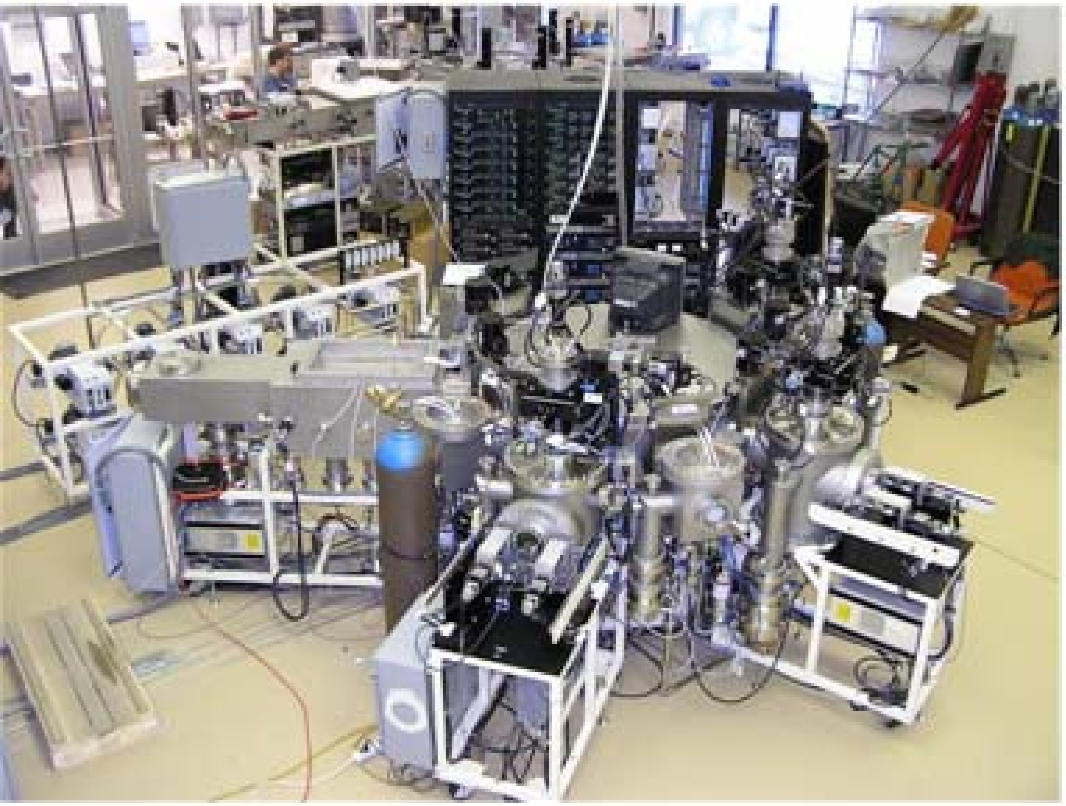
NREL
Emulating Industry
1.5μm in 6 min η~5%

NREL
Closing the Gap
2 μm in 6 min η >15%



PDIL

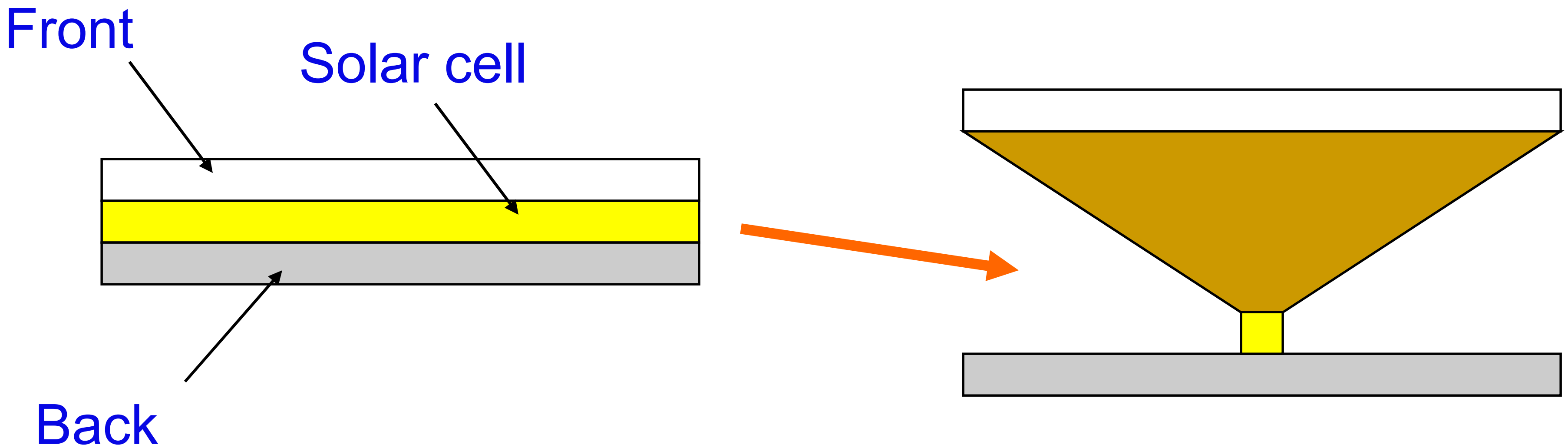
Process Development and Integration Lab



- 11000 sq ft, 6 bays
- Silicon Thin-Film Cluster Tool
- Future deposition and analytical tools
- Visiting Industry Process Prototypes

Concentrating Photovoltaic Systems

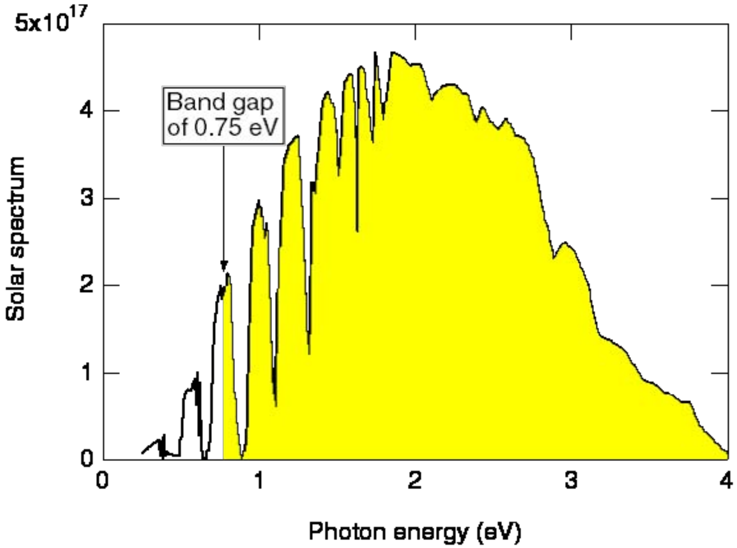
Industry growth is currently constrained by Si availability
Reduce semiconductor material by concentrating the light



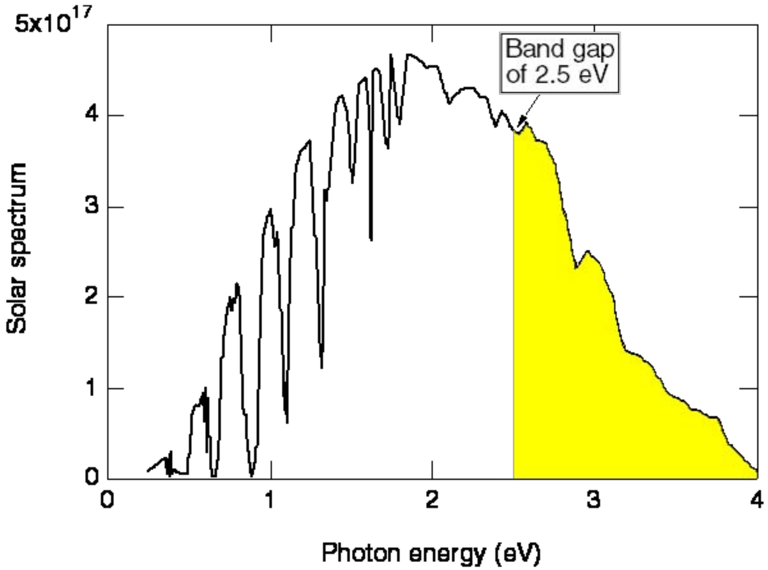
Concentration:

1. Reduces semiconductor use
2. Allows use of higher efficiency cell (higher system efficiency)

Why multijunction?
Power = Current X Voltage



High current,
but low voltage
Excess energy lost to heat

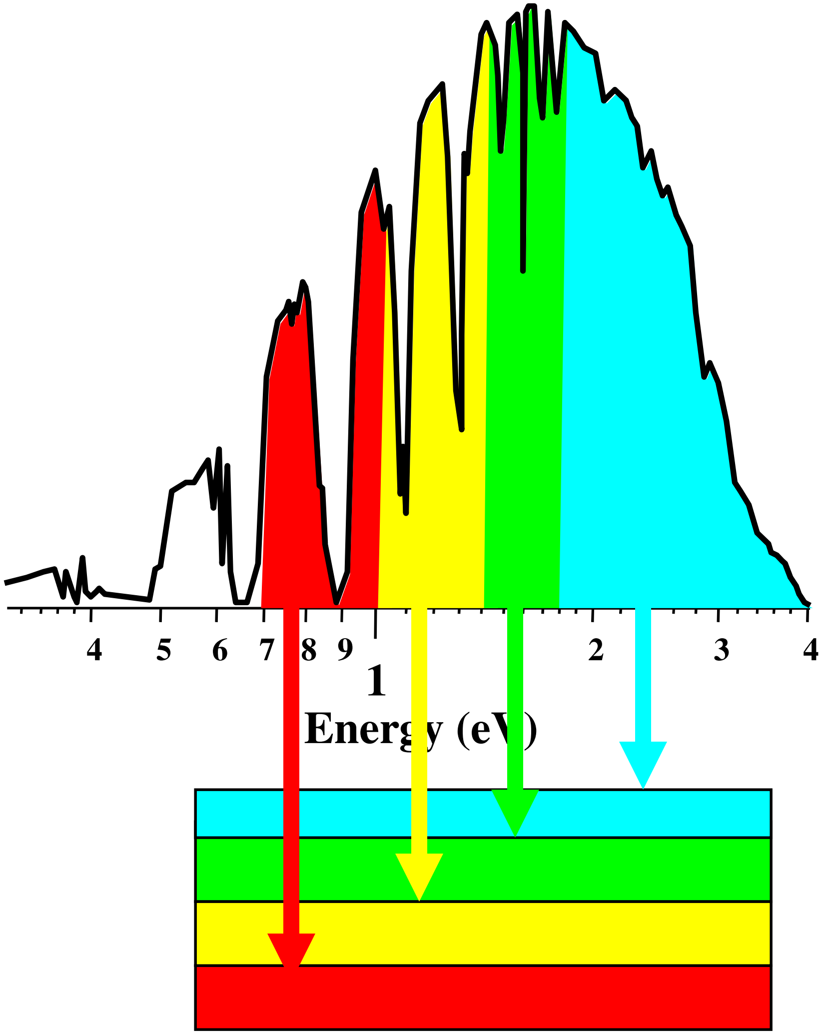


High voltage,
but low current
Sub-bandgap light is lost

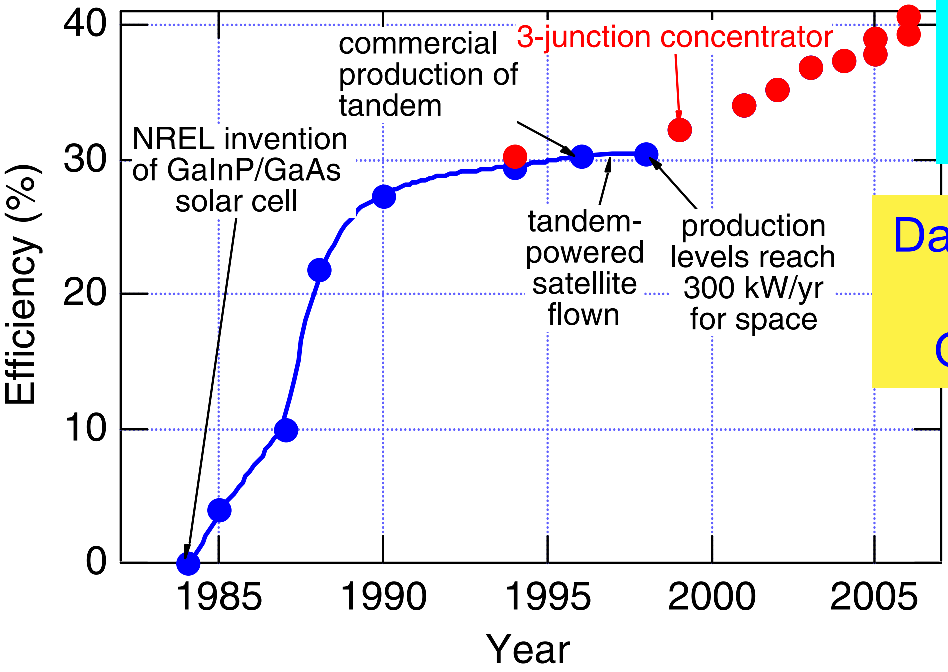
Highest efficiency: Absorb each color of light with a material that has a band gap equal to the photon energy

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

Multijunction cells use multiple materials to match the solar spectrum



Success of GaInP/GaAs/Ge cell



40.7%
King, APL
2007

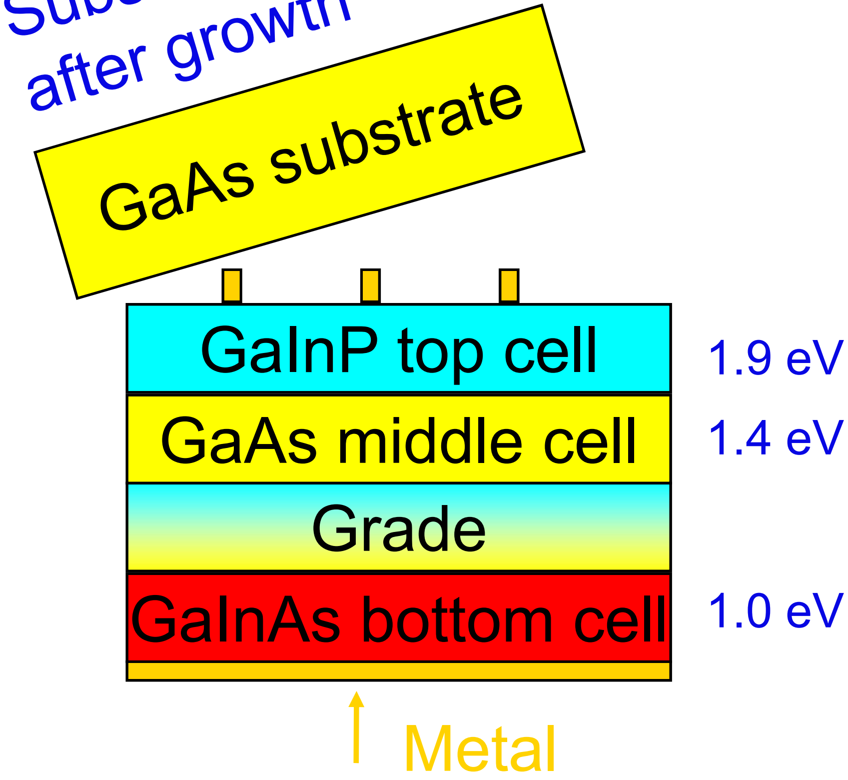
Dan David Prize
2007
Olson, Kurtz

Mars Rover powered by multijunction cells

This very successful space cell is currently being engineered into systems for terrestrial use

High-efficiency mismatched cells

Substrate removed after growth



GaAs substrate

GaInP top cell 1.9 eV

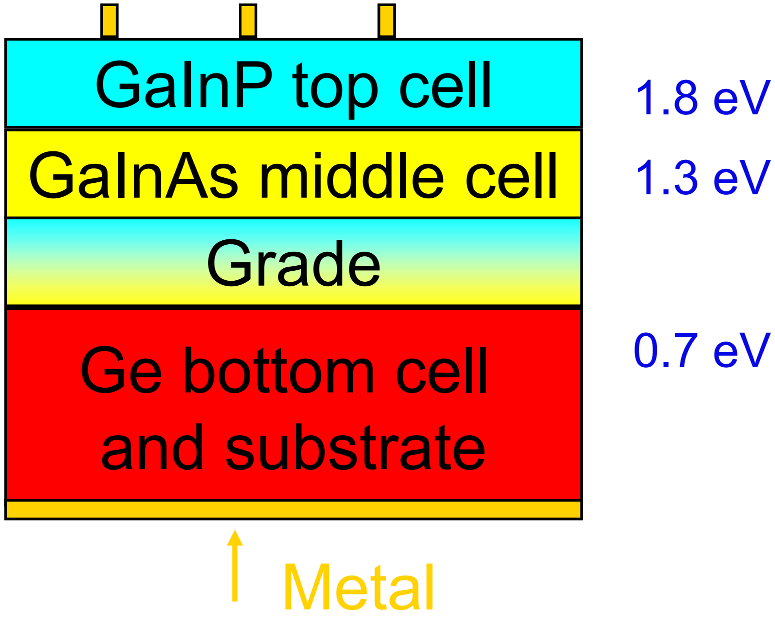
GaAs middle cell 1.4 eV

Grade

GaInAs bottom cell 1.0 eV

Metal

38.9% @ 80 suns
Geisz, 2007



GaInP top cell 1.8 eV

GaInAs middle cell 1.3 eV

Grade

Ge bottom cell and substrate 0.7 eV

Metal

40.7% King, 2006

New research: from 40% to 50%

Refractive optical designs

Fresnel lenses focus
light on small cells
Passive cooling

Small lenses and small cells
can lead to thin designs and
“flat-plate” cooling

Multijunction CPV industry press

- **Cell orders**
  - **Spectrolab to Solar Systems - 11 MW, announced Aug. 2006**
  - **Spectrolab to SolFocus - >10 MW, announced Aug. 2006**
  - **EMCORE to Green & Gold Energy - $24M for 105 MW; delivery by end of 2008**
- **Planned projects**
  - **Solar Systems 154 MW for $420M, completion 2013**
  - **Green & Gold reports orders for 430 MW**
  - **GreenVolts - 2 MW for PG&E; 1st phase in 2008, completion 2009**
  - **~2 MW in Spain: SolFocus, Concentrix, Isofoton**

NREL CPV

- New higher performance cell development
- Systems driven component design
- Cell and module reliability
- Facilitate development of codes and standards
- Concentrator industry resource center

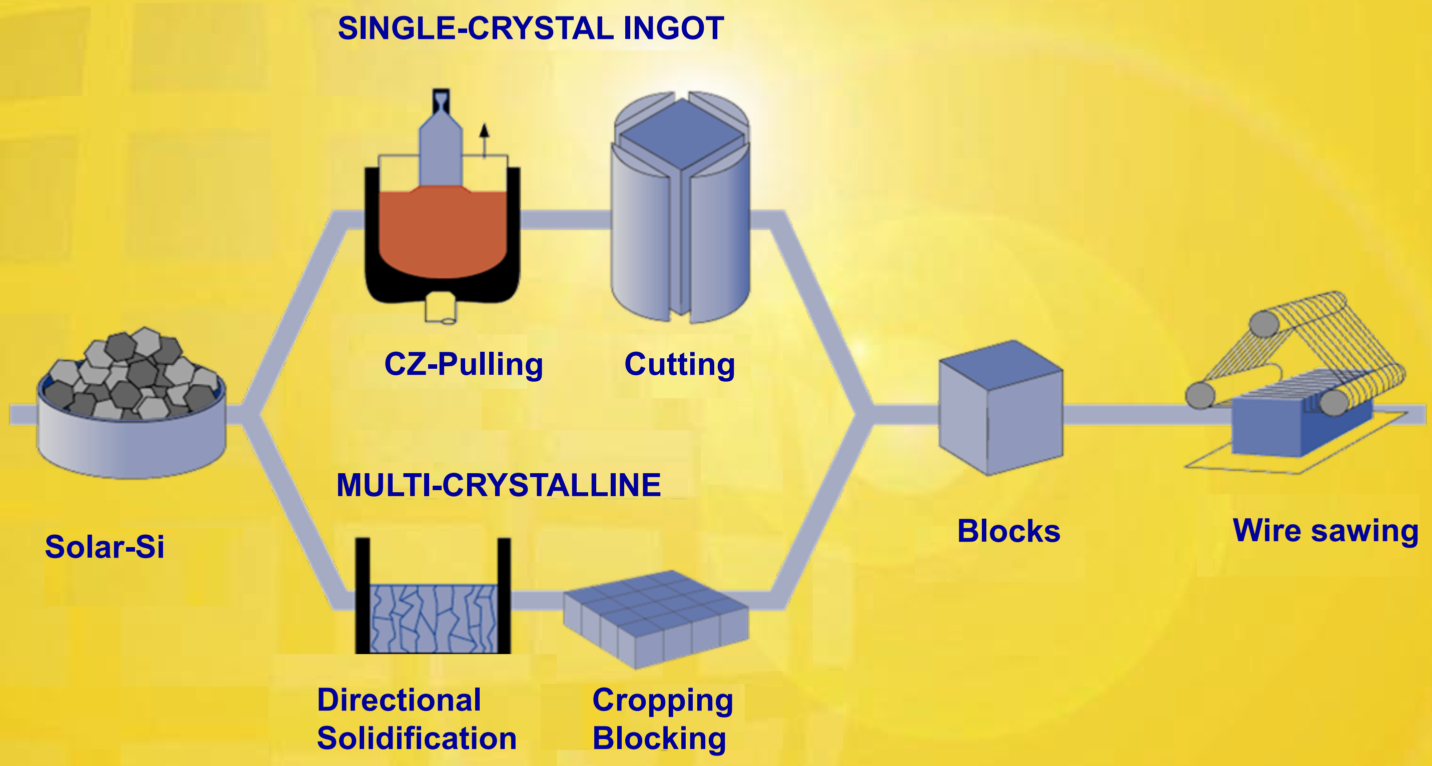
PV is not your typical electronics business

Dealing with the Silicon Shortage

2005 Module Production of 1.7 GW

- Consumed
  - Half of the electronic grade Si (15,000 tons)
  - 200,000 tons glass
- Contributed < 1% of electronics sales $
- Delivered <0.01% of global electricity kWh

Total Silicon Yield From Feedstock To Wafer 32-54%



SINGLE-CRYSTAL INGOT

CZ-Pulling

Cutting

Solar-Si

MULTI-CRYSTALLINE

Directional Solidification

Cropping Blocking

Blocks

Wire sawing

Silicon Yield:	90%-95%	80%-95%	45%-60%
Si-Recycle:	Pot Scrap	Cropped Section (Tops and tails,slabs)	Broken Wafer

Maintaining the Growth Rate in Silicon PV

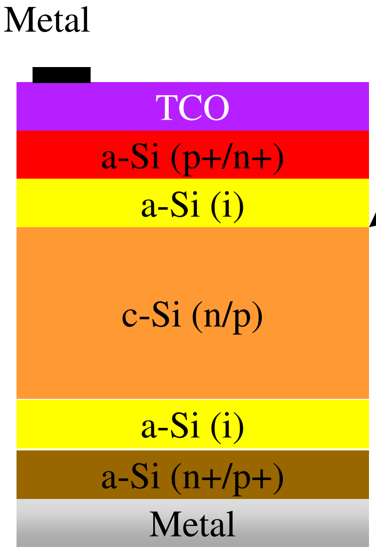
- By 2010 PV will take 2/3's of 80,000 MT pure silicon supply
  - Leading Si suppliers plan to double production by 2010 in conventional Siemens process 32,000 MT → > 64,000 MT
  - New production technology using directional solidification or chemical/physical treatment of metallurgical grade Si (Elkem, Dow Corning, and others) will add 10,000 to 15,000 MT
- Higher cell efficiency, thinner wafers and improved yield will reduce consumption of Silicon to < 3 g/W

Processing thin wafers presents new challenges to avoid bowing and breakage

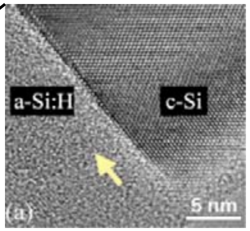
- Low temperature processes
- Minimize mechanical contact
- Balance strain
- Texture
- Surface passivation
- Improved contacts

100 µm Thin and Flexible Wafer as Cut

Silicon Heterojuncton cell

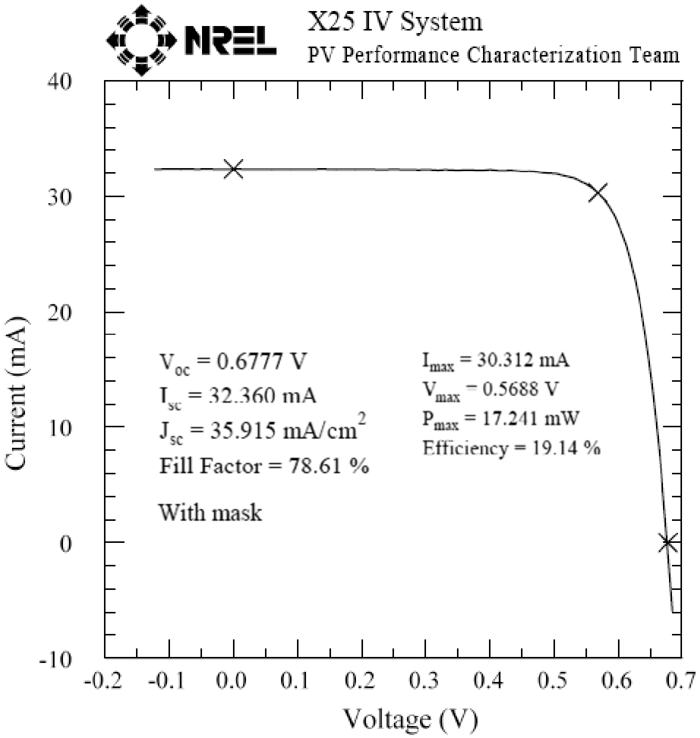


c-Si sandwich between thin Si layers



Thin Si layers were deposited by HWCVD or PECVD

19.1% on 0.9 cm^2 FZ p-type c-Si

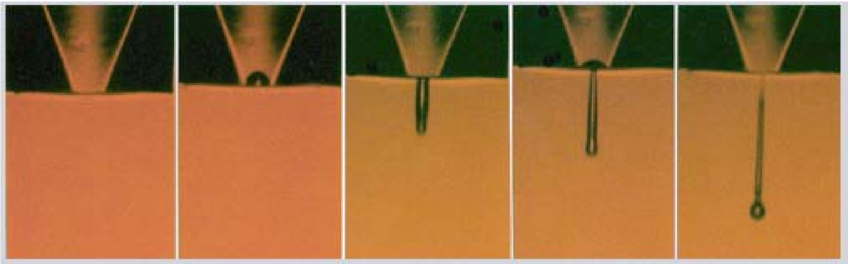


V_{oc} = 0.6777 V
I_{sc} = 32.360 mA
J_{sc} = 35.915 mA/cm^2
Fill Factor = 78.61 %

With mask

I_{max} = 30.312 mA
V_{max} = 0.5688 V
P_{max} = 17.241 mW
Efficiency = 19.14 %

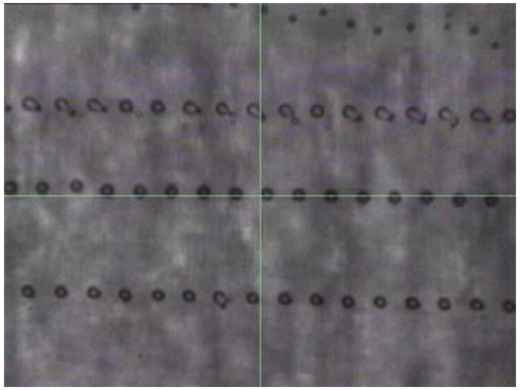
Printing of Nickel (Piezoelectric Printing)



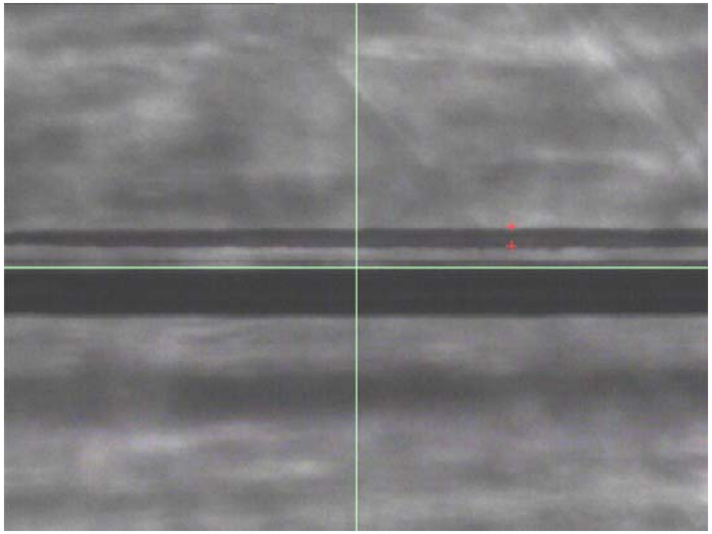
Dimatix Printer

Piezoelectric inkjet

Drop formation



35 µm Nickel drops on glass

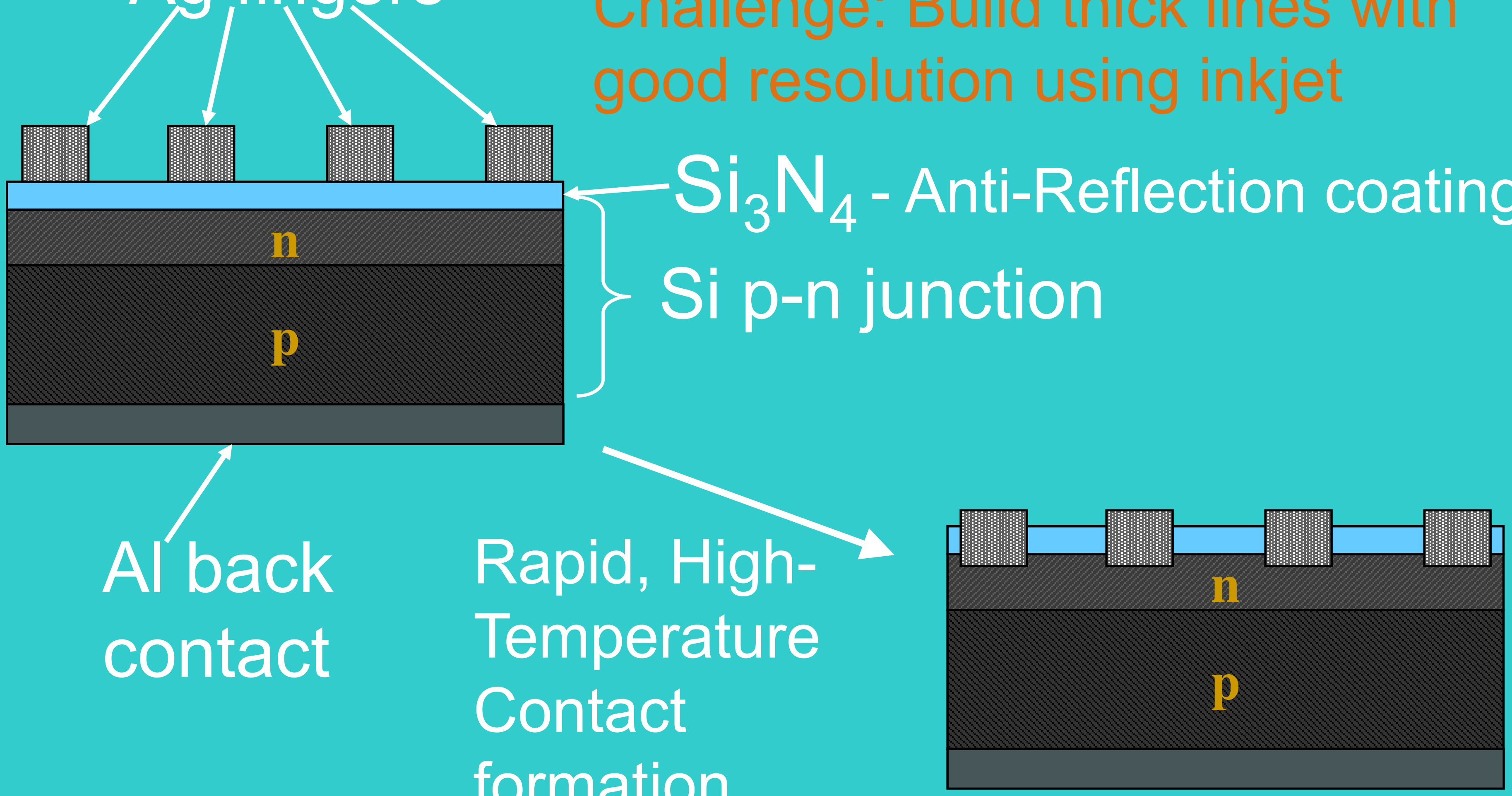


50 µm wide Nickel line on glass

Si Solar Cell Contact Formation

Fingers currently screen printed

Challenge: Build thick lines with good resolution using inkjet



Ag fingers

Si_3N_4 - Anti-Reflection coating

Si p-n junction

Al back contact

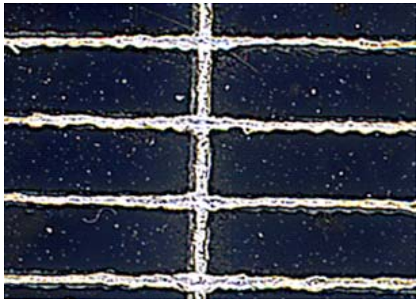
Rapid, High-Temperature Contact formation

Solar Cells with Printed Contacts

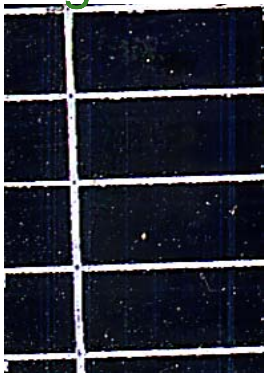
	1st	2nd	3rd	Goal
Line thickness:	10 µm	15 µm	15 µm	15 µm
Line width:	400 µm	250µm	220µm	<100µm
Dep. temperature :	180°C	180°C	180°C	180°C
Ann. temperature:	850°C	850°C	750°C	750°C
Cell efficiency	8%	8%	10%	15%

AR-coated Si substrates from Evergreen Solar

1st generation



2nd generation

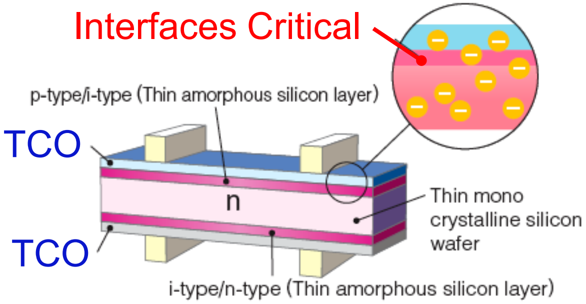


Improved processing recently produced a 12% efficient cell

Combinatorial Optimization of TCOs for Wafer-Si Heterojunction Cells

Goal: Improved TCOs for:
- Materials Compatibility
- Interfaces
- Transparency, Conductivity

2-Sided Heterojunction Cell

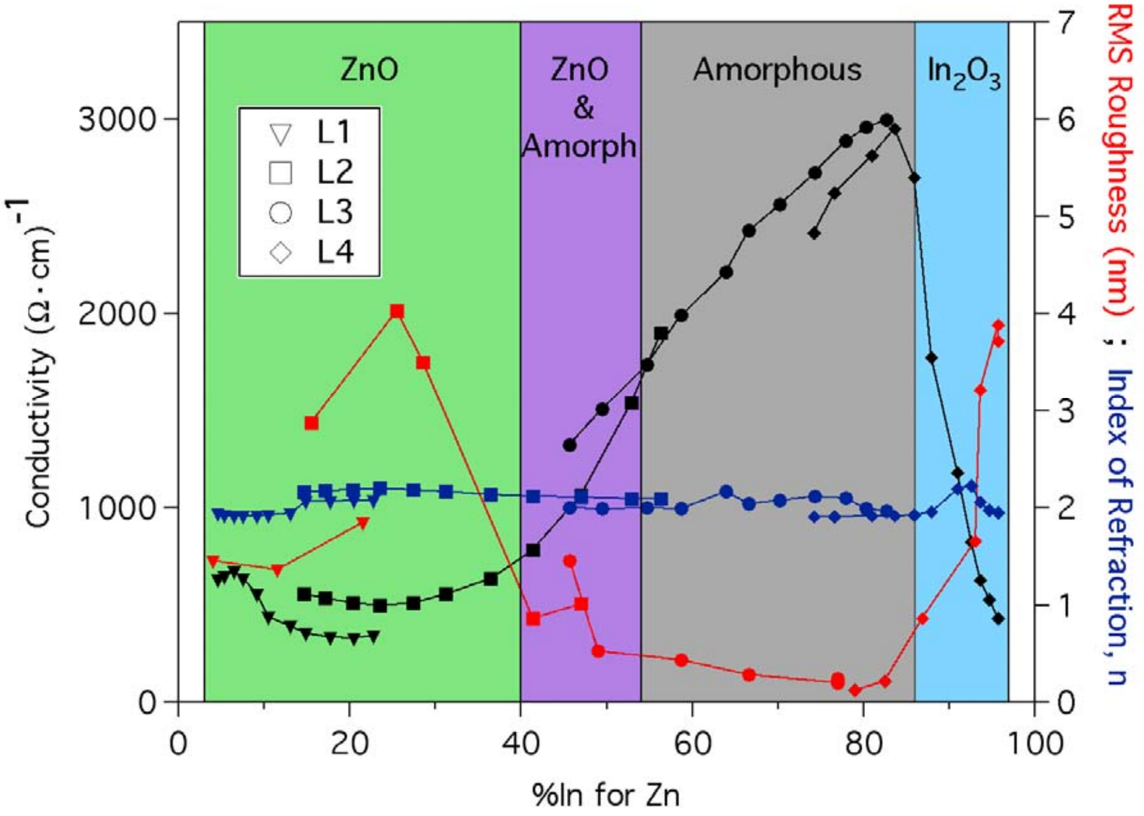


Materials: In-Zn-O, Ga:ZnO

- InZnO:
  - High Conductivity (σ = 3000 S/cm, 5000 reported May 2007)
  - Smooth (R_{RMS} < 0.5 nm)
  - Ambient Temperature Deposition (No Interface Diffusion)

Approach:
- Composition Spread Sputtering w/Substrate Bias to Control Ion Damage
- Single Composition Sputtering For Further Optimization

As-dep IZO: Conductivity, Structure, Roughness & Refractive Index



a-IZO (80/20)

σ = 3000 Ω^{-1} - cm^{-1}

R_{RMS} < 0.5 nm

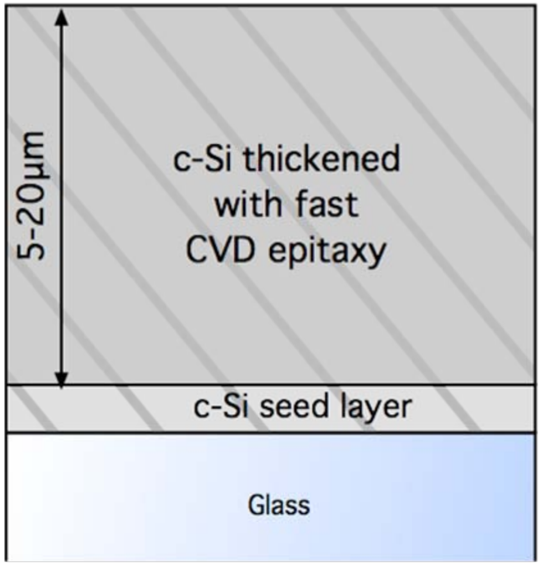
Conductivity maximum occurs in smooth amorphous region and mobility is ~40 cm^2/Vsec across the amorphous region

Avoid high wafer costs with film silicon

An ideal PV material would be 20 μm of crystal silicon on glass!

NREL approach to crystal silicon on glass

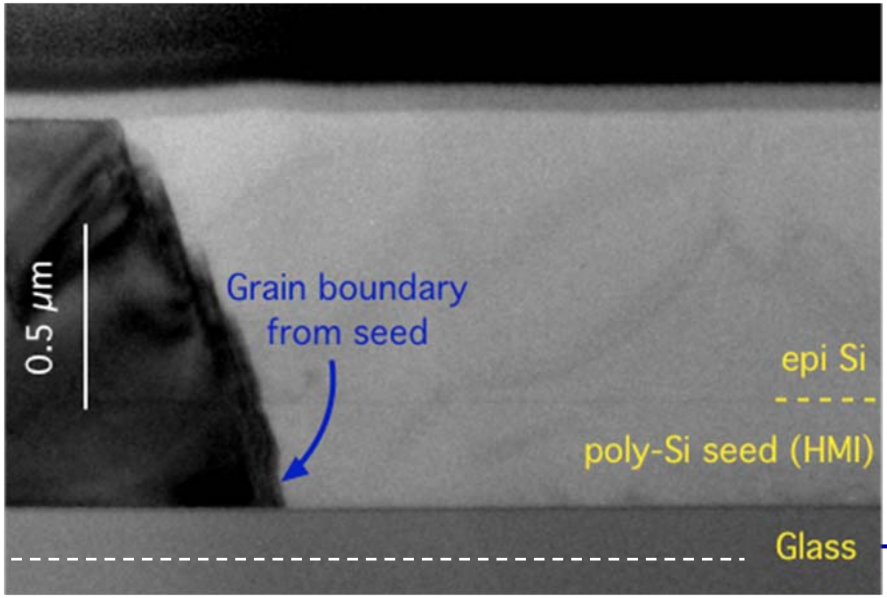
- Initial step: establish good crystal quality with a thin seed layer
- Second step: Quickly thicken the seed layer epitaxially



Research Challenges

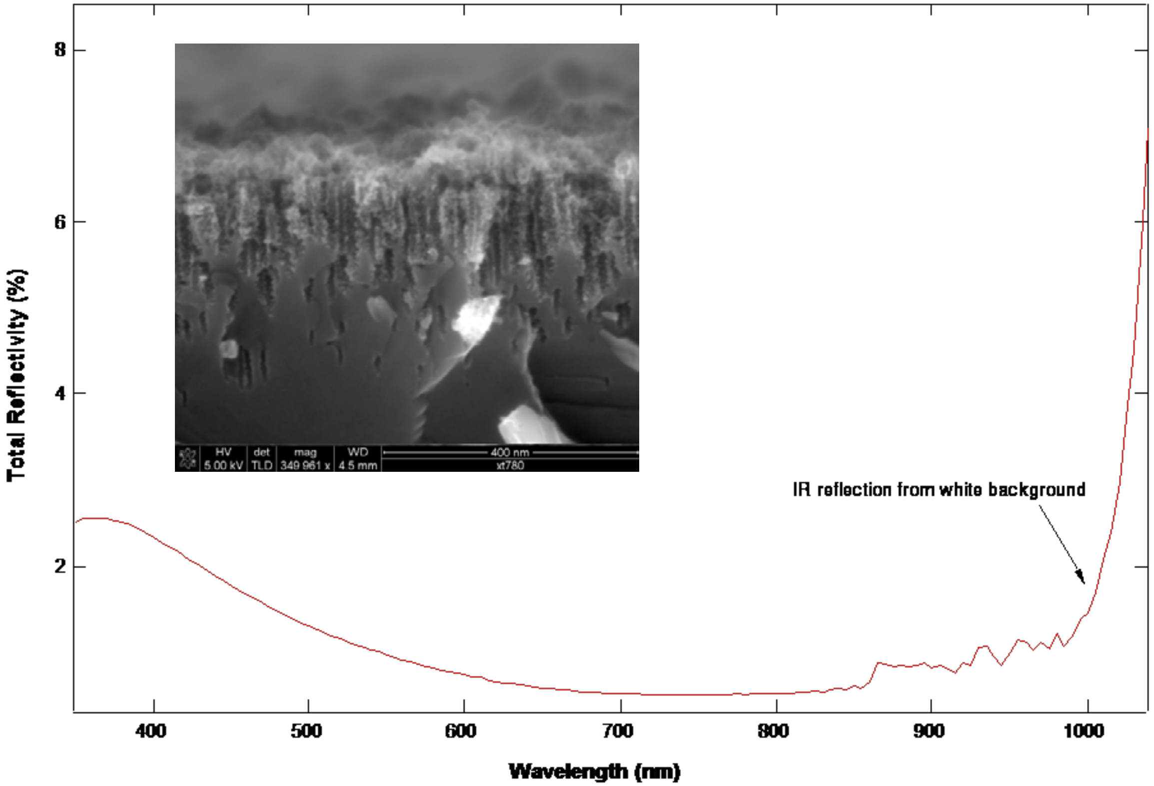
- High quality epitaxy at glass-compatible temperatures
- Identification of high-quality, low-cost seed layers
- Final device designs
  (*p*/*n* junction, light trapping, electrical contacts)

Demonstrate Epitaxy on seed c-Si/glass



- Demonstrated epitaxy on poly-Si seed
- High quality epitaxy
- Material quality is limited by grain boundaries in the seed layer

“Black silicon” anti-reflection



- Rapid, inexpensive, process invented at NREL
- Cross-sectional TEM shows continuous density gradient

NREL Photovoltaic Technologies

- Portfolio Balance
  - Product solutions
  - Technology development
  - Exploratory research
- Partnership Opportunities
- Facility Access
- Measurements and Characterization Support
- Reliability Testing and Accelerated Life Tests

Solutions, Science and Advanced Concepts