Australian-U.S. PV Research at UNSW

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Australian-U.S. PV Research at UNSW

- Major US PV Research Programs
  - National Renewable Energy Laboratory (NREL)
  - New National Science Foundation- Department of Energy - Engineering Research Center at Arizona Sate University
- PV Research at UNSW
- New High Performance PV Research at UNSW
- **Collaboration Opportunities for Australian-U.S. PV Research**

QESST

Quantum Energy and Sustainable Solar Technologies

NSF-DOE Announcement

August 17, 2011

The National Science Foundation (NSF) announced an award to Arizona State University and its partners to establish a new Engineering Research Center (ERC) jointly funded by NSF and the Department of Energy (DOE): the **NSF--DOE ERC for Quantum Energy and Sustainable Solar Technologies (QESST)**. QESST will develop interdisciplinary research and education programs to address the realization of a large-scale, sustainable, domestic energy source -- by developing advanced solar photovoltaic technologies and by providing the foundation for new industries through innovation. **Over the next five years, the NSF ERC program and the DOE Solar Energy Technologies program together will invest $18.5 million in the Center**.

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NSF-DOE Announcement (2)

August 17, 2011

Over recent decades, engineers and scientists have investigated a number of approaches to harness the nearly boundless energy of the sun. They have pursued photovoltaic arrays that are energy-efficient, easy to manufacture, and environmentally friendly. Technological advances have allowed photovoltaic applications to expand, but thus far they have enabled solar energy only to supply less than one percent of the electrical energy needs of the United States. QESST proposes to develop the technologies and manufacturing processes to dramatically increase the amount of solar photovoltaic energy supplying the nation's homes and businesses.

QESST Vision

To exploit one of the greatest scientific advances of the 20^{th} century - quantum mechanics - to develop photovoltaics (PV) that will:

Increase the sustainability, accessibility and functionality of electricity generation systems;

Renew interest in science and engineering; and

Revitalize the US PV industry.

QESST

- QESST will combine fundamental materials research in silicon, thin film, and tandem solar cells with systems-level issues of manufacturability and integration. QESST researchers will consider sustainability and resource constraints to inform material and technological choices. In addition, the Center will educate a new generation of engineers in solar energy technologies and manufacturing techniques and equip them to be renewable energy innovators.
- The NSF-DOE QESST ERC will be based at Arizona State University, in partnership with the California Institute of Technology, the Massachusetts Institute of Technology, the University of Delaware, and the University of New Mexico. Researchers at the Imperial College, London, the University of New South Wales in Australia, and the University of Tokyo will contribute additional expertise and international perspectives.
- The involvement of nearly 40 industry partners -- including multinational corporations, manufacturers, and start-up firms -- will spur innovation and provide university students with first-hand experience in entrepreneurship.

NSF-ERC

- Since 1985 the NSF ERC program has fostered broad-based research and education collaborations to focus on creating technological breakthroughs for new products and services and on preparing U.S. engineering graduates to successfully participate in the global economy. The four centers launched this June, as part of the third generation of NSF ERCs, place increased emphasis on innovation and entrepreneurship, partnerships with small research firms, and international collaboration and cultural exchange.

- "The Gen-3 ERCs are designed to speed the process of transitioning knowledge into innovation and to provide young engineers with experience in research and entrepreneurship to strengthen their role as innovation leaders in the global economy," said Lynn Preston, the leader of the ERC Program. "Building on the rich understanding we gained from two previous generations of ERCs, we expect these new centers to make even more significant impacts on the competitiveness of U.S. industry."

Overview of QESST

- The QESST ERC Team
- Vision and Broader Impact
- Strategic Plan
- Research, Thrusts, and Testbeds
- Education and Outreach
- Industry and Entrepreneurship
- Infrastructure: Leadership, Diversity, Management, and Financial Support

Vision

To exploit one of the greatest scientific advances of the 20th century—*quantum mechanics*—to develop photovoltaics (PV) that will meet the Terawatt (TW) Challenge

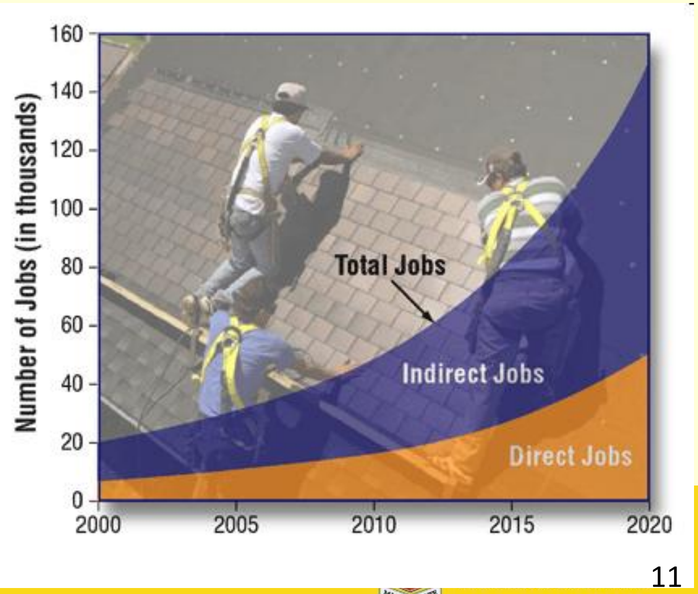
- Sustainable electricity generation: economic, environmental, and societal
- Renew interest in science and engineering education
- Revitalize the U.S. PV industry through innovation and collaboration

Broader Impact

PV is "a great opportunity disguised as a set of insoluble problems." – Thomas Friedman

Impact: PV industry is at a tipping point, where advances rely on innovation and will impact society, science, technology, education, and industry

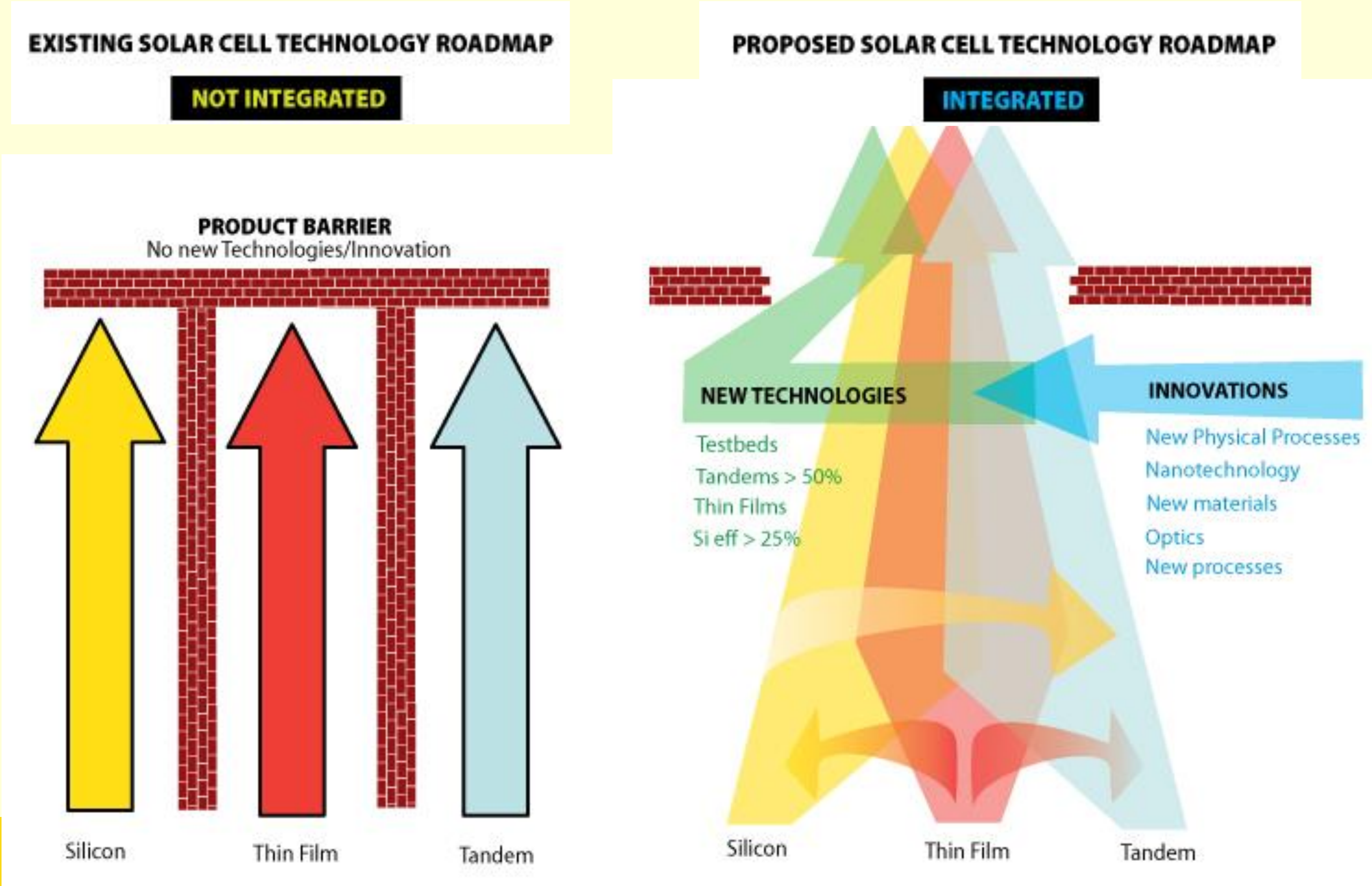
- Advance discovery while promoting teaching, training, and learning
- Broaden participation of underrepresented groups
- Enhance infrastructure
- Broaden dissemination to enhance scientific and technological understanding
- Societal Impact
    - Results in growth in new business, jobs, and entrepreneurship
    - Rallies national solar energy leaders, companies and resources
    - Environmental impact
    - Renewed interest in science and engineering



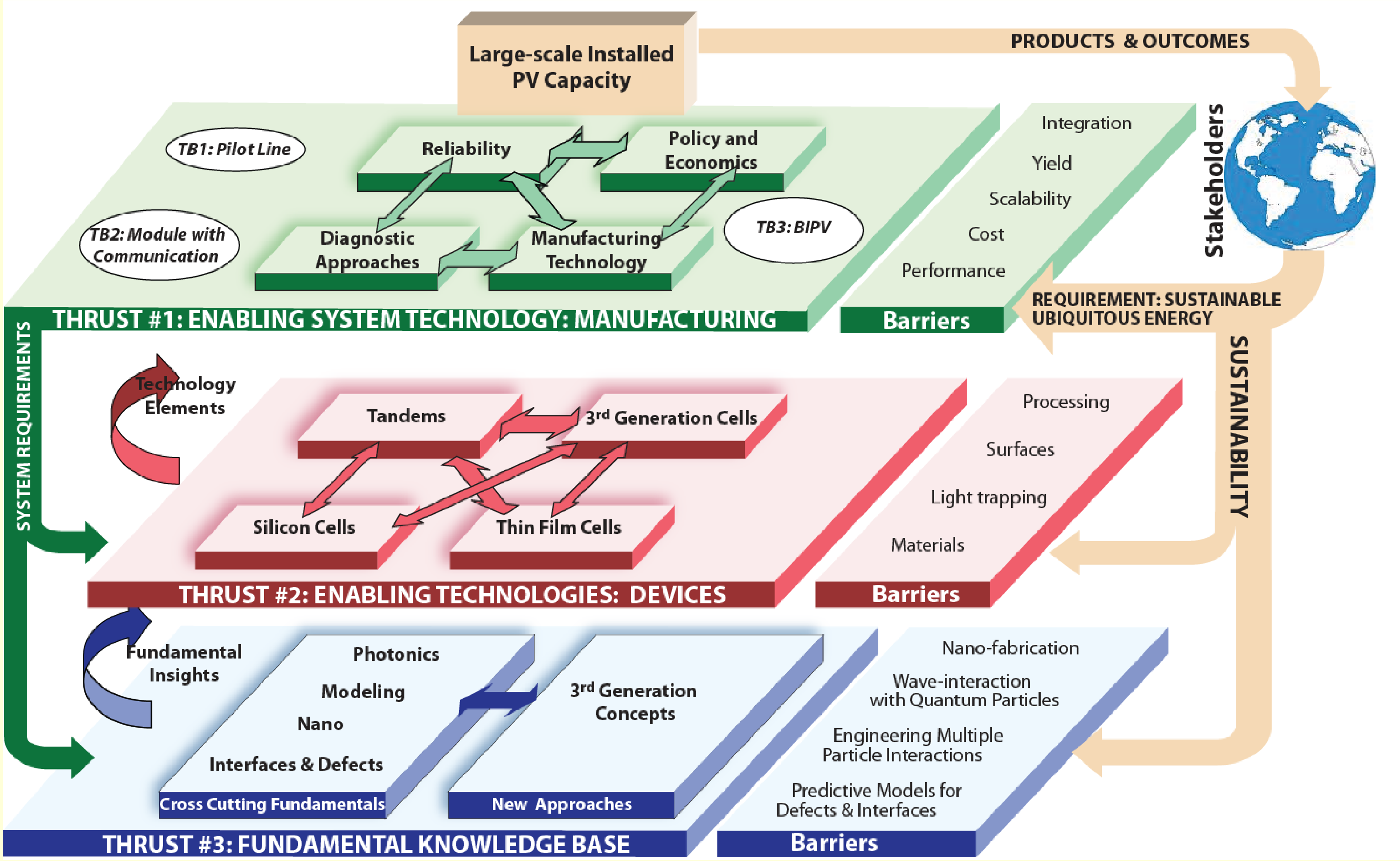
Strategic Plan

- Focused on TW Challenge to address the barriers to sustained and rapid growth in PV
- Systems-driven roadmap that allows evolutionary path to revolutionary devices
  - Increased efficiency while decreasing material usage and/or costs
- Cross-pollination: integration of advantages from different technologies and disciplines

Integration and Technologies



Strategic Plan: 3-Plane Diagram



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Education/Outreach

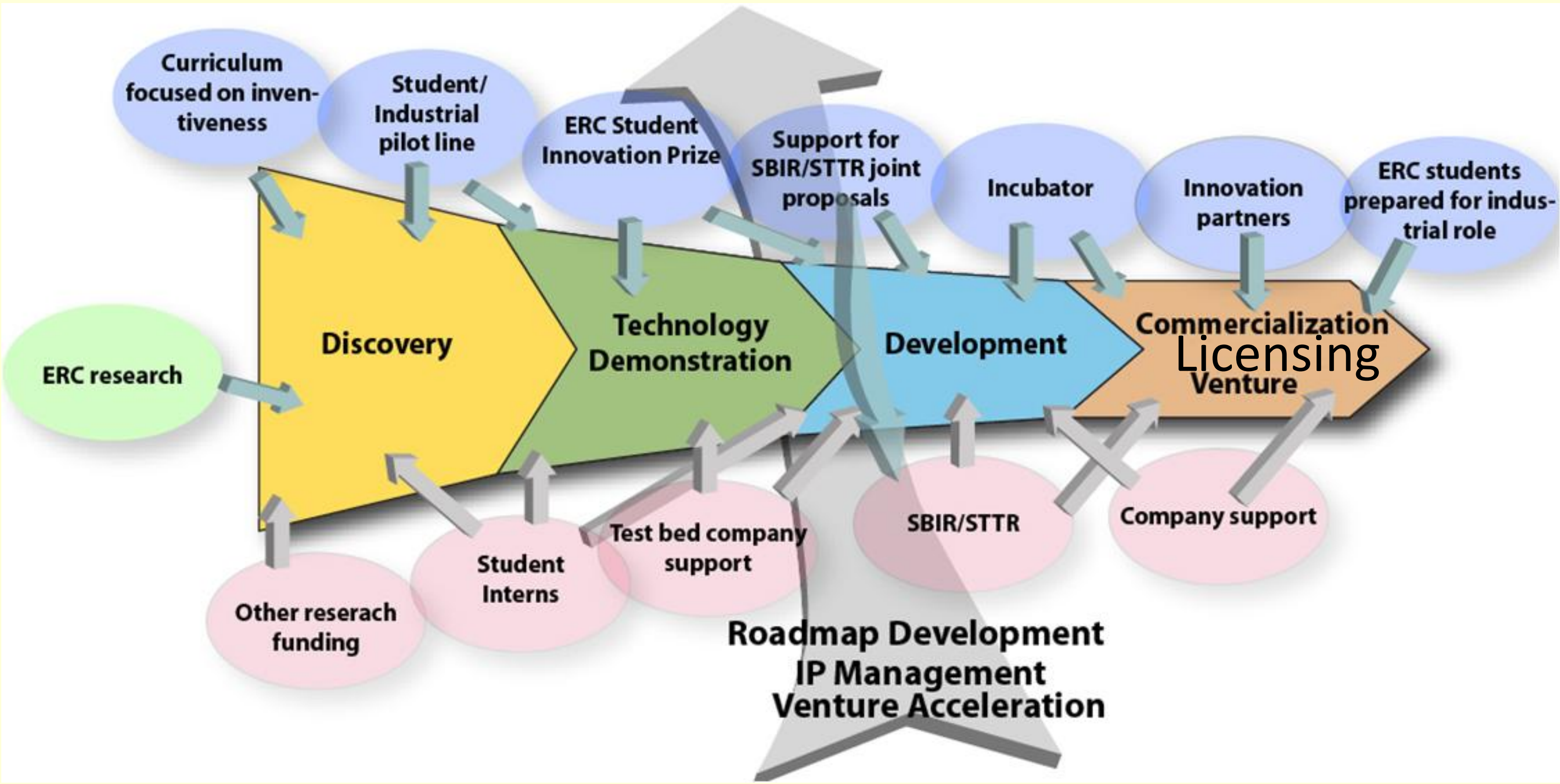
Developing Diverse Adaptive and Creative Innovators

- Partnership with School of Education
- Renewable energy curriculum development
  - Vertically integrated online education materials
  - Problem-based learning guides
- Mentorship
  - Structured research experiences for undergraduates
  - Student-led pilot line
  - Industry-based partnerships—from internships to solar decathlon
- Community and service-learning programs
  - Testbeds create opportunities for structured service-learning projects with industry
  - Educating global engineers
- Pre-college Young Solar Learning program to support recruitment and retention of highly qualified engineers
- Assessment to guide development
- Engineering hired six faculty focused on education

K-12 Resources

- Existing Young Scholar Program
  - MESA
  - GK-12 programs
- Existing cyber-infrastructure
- Research experience for teachers
- Strong existing long-term partnerships with school districts and teachers

Innovation – Concept to Commercialization



School of Photovoltaic and Renewable Energy Engineering

Australia-based Education and Research for Photovoltaics Industry

R. Corkish, Head of School

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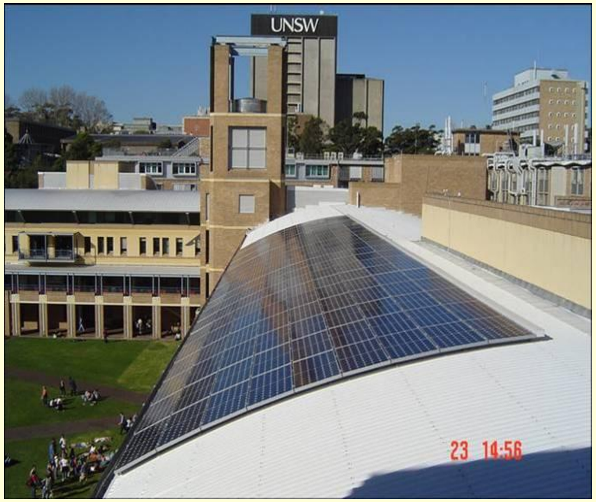
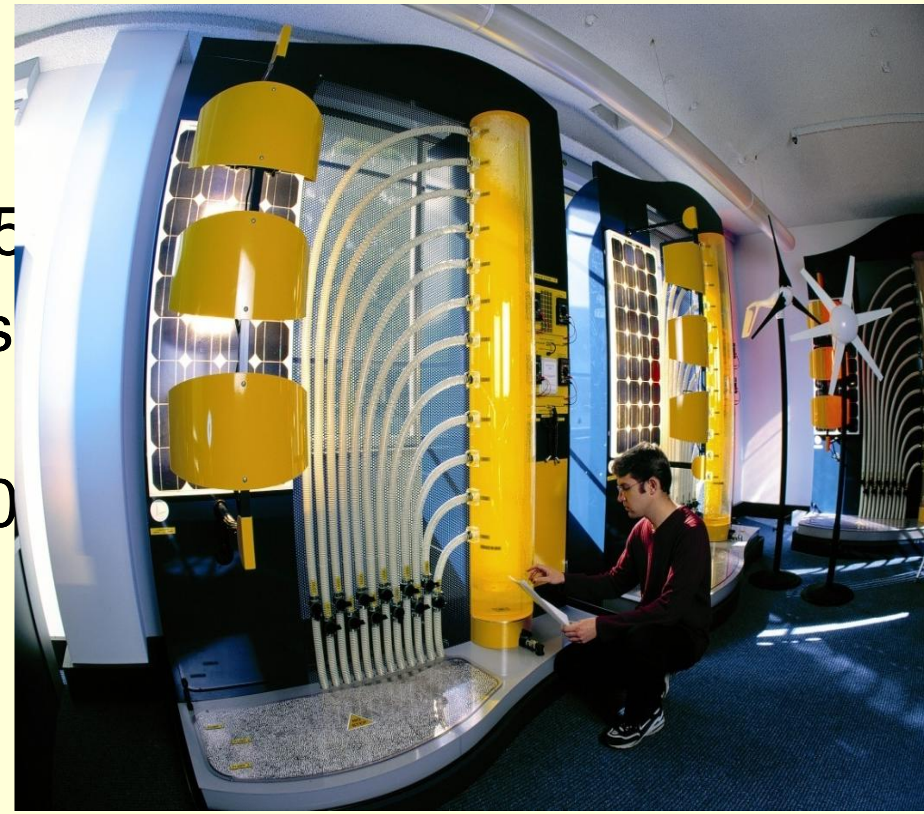
UNSW

- Established 1949
- Member Group of Eight best Australian research universities
- Member Universitas21 - leading research intensive universities in 13 countries
- Focus on environmental sustainability
- 46,630 Students in 2009
  - 69% undergraduate
  - 24% postgraduate coursework
  - 7% higher degree research
  - 25% international
- 2,497 Academic Staff
- 2,779 Professional & Technical Staff
- 200,847 alumni in 2008
- 8 faculties; 56 schools
- Kensington site is 38 ha



School History

- PV research within UNSW Electrical Eng. 1974 – 1998
- Separate Centre 1999 – 2005
- Pioneering UG photovoltaics engineering program 2000
- PG coursework program 200
- Second UG program 2003
- New School declared 2006



Undergraduate Education

Two 4-year Engineering programs (473 students):

- Photovoltaics and Solar Energy (started 2000)
- Renewable Energy (started 2003)
- 8% growth 2010-11

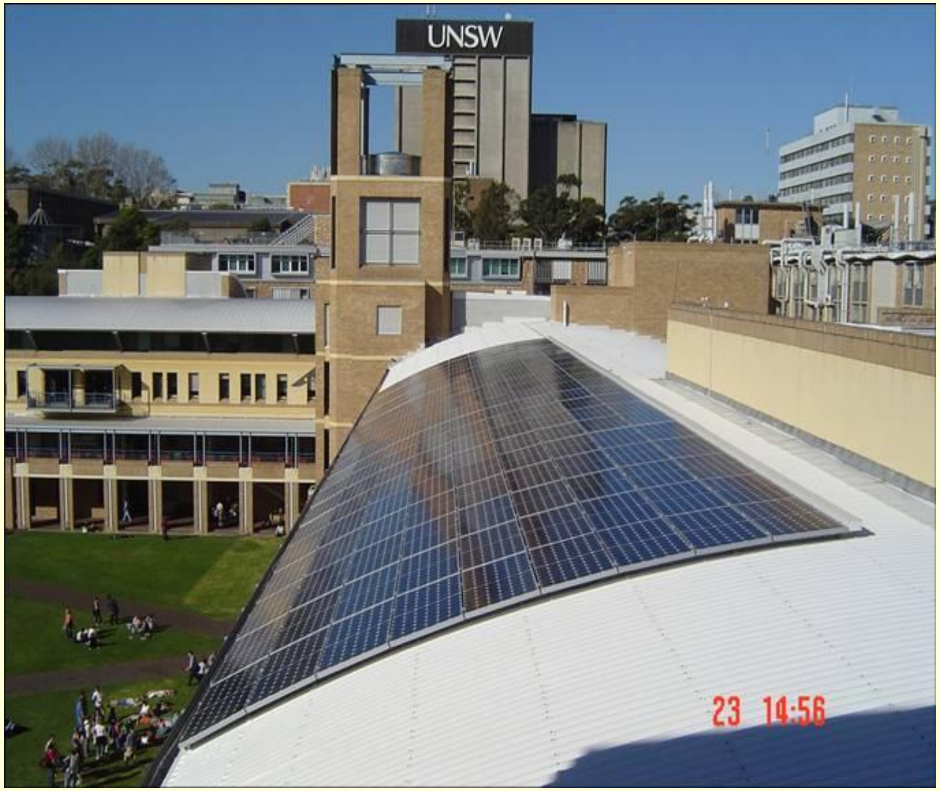
- 232 graduates
  - 160 PVSE
  - 9 PVSE + Science
  - 13 PVSE + Arts
  - 4 PVSE + Commerce
  - 44 RE
  - 2 RE + Science

(Session 2, 2011 figures)

Photovoltaics and Solar Energy

First such specialist degree globally

- Technology development
- Manufacturing
- Systems engineering
- Maintenance
- Reliability and lifecycle analysis
- Marketing
- Policy

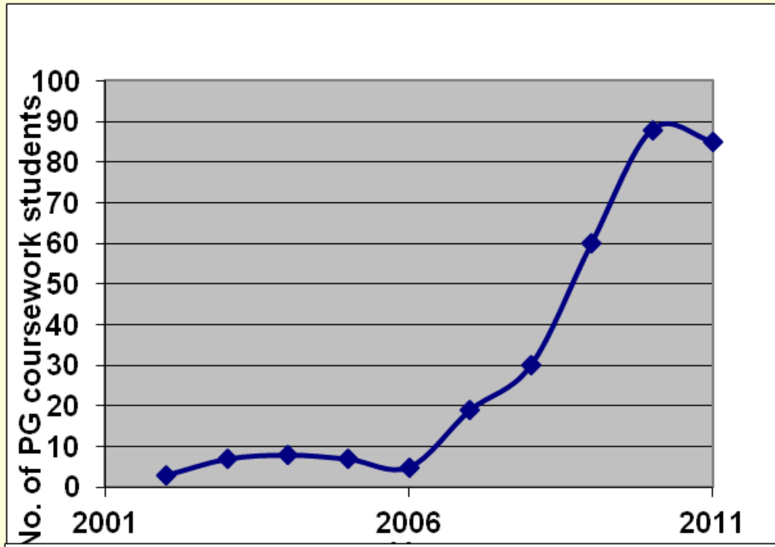


Renewable Energy Eng.

- Begun 2003
- Development shared with Murdoch Univ., Perth
  - Photovoltaics
  - Energy Efficiency
  - Solar thermal
  - Wind
  - Biomass
  - Solar architecture

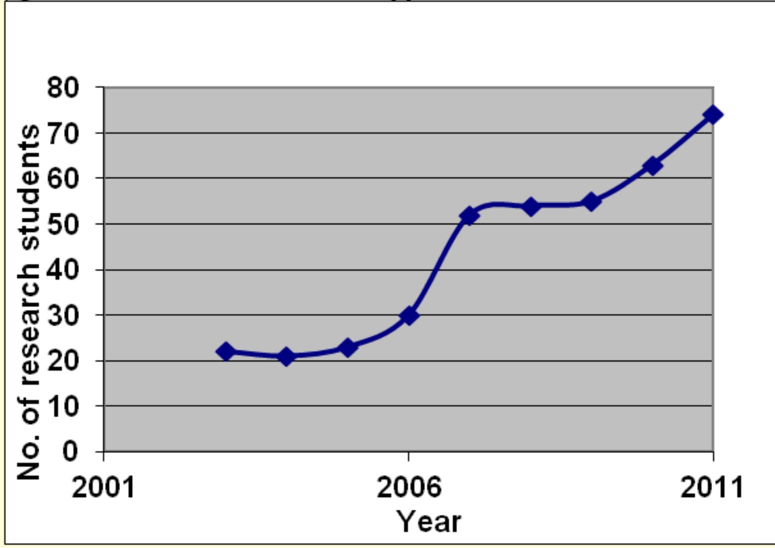
Postgraduate Education

- **Master of Engineering Science in Photovoltaics and Solar Energy** **(85 students)**
  - Rapid growth 2007-10
  - Strong AUD in 2011
  - 1.5 year addition to 4-year BEng. or 4-year BSc

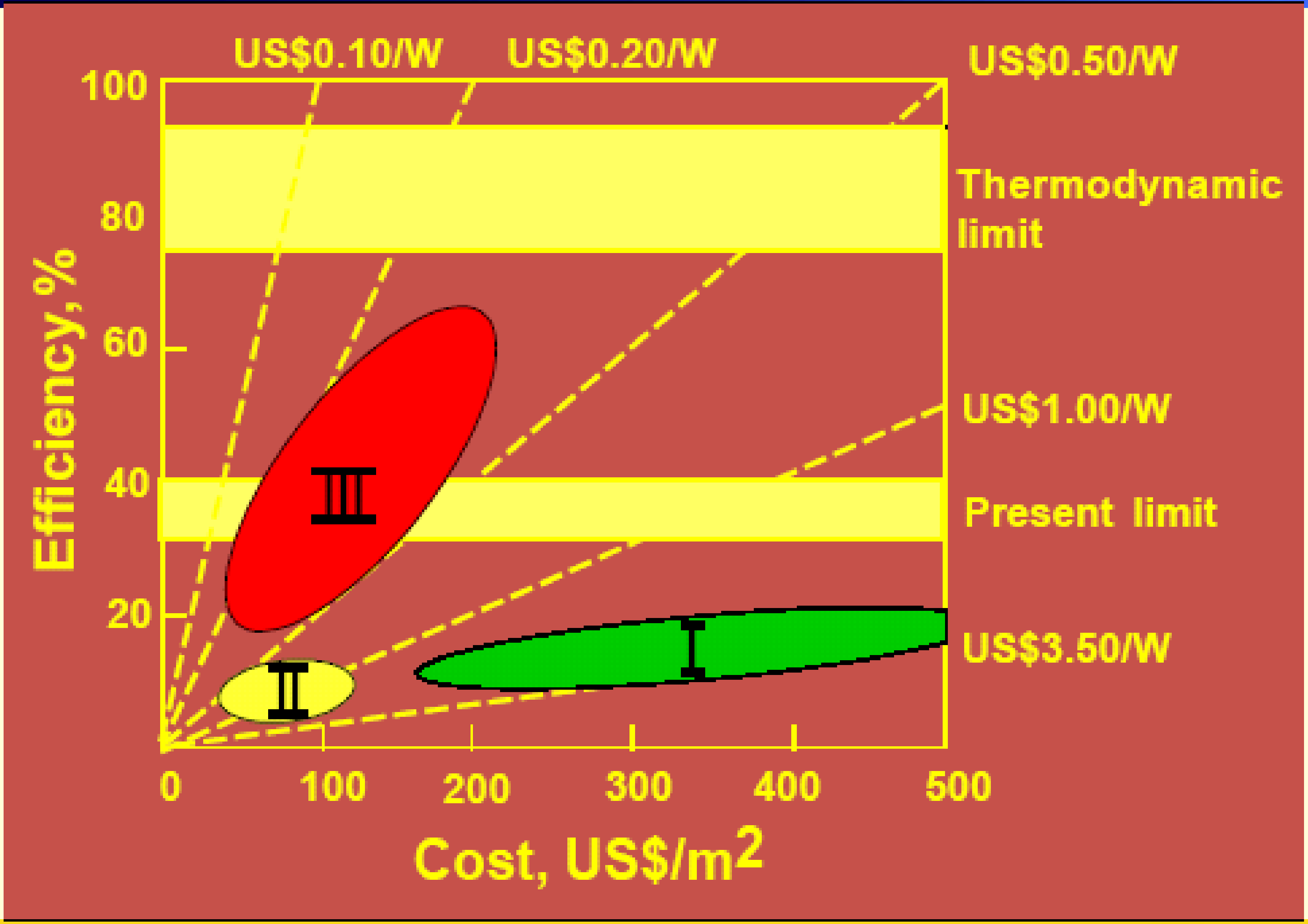


- **Research degrees**
  - PhD (66 students),
  - Masters Research (8 students)
  - Historically through Electrical Eng.

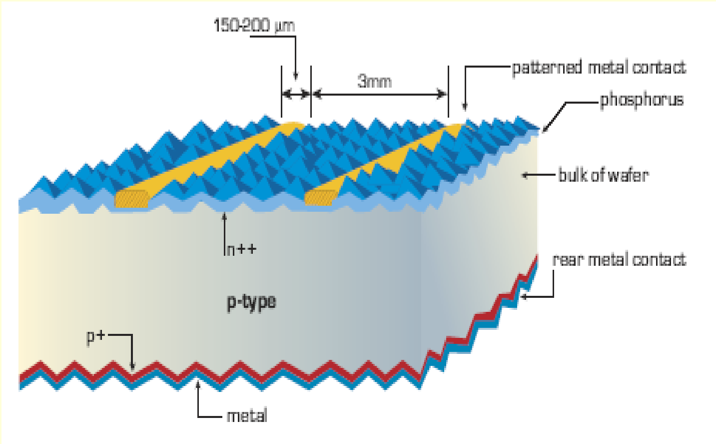
(S2, 2011 figures)



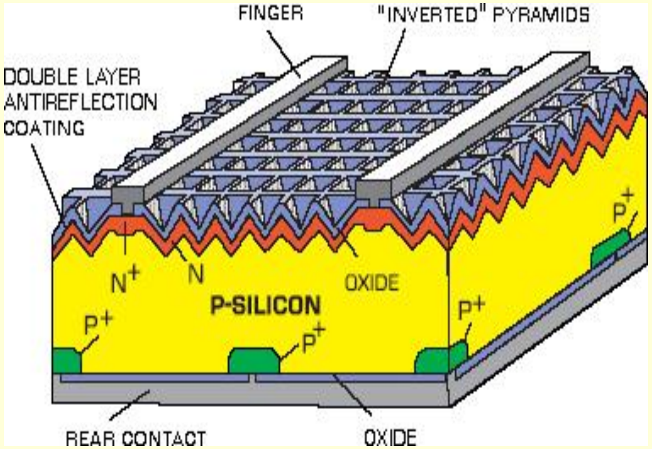
Generations of Photovoltaics



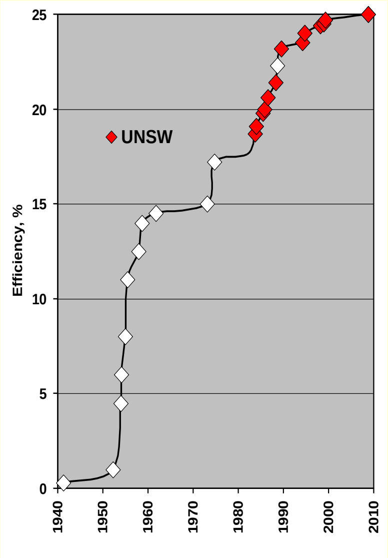
First Generation: Wafers/Ribbons



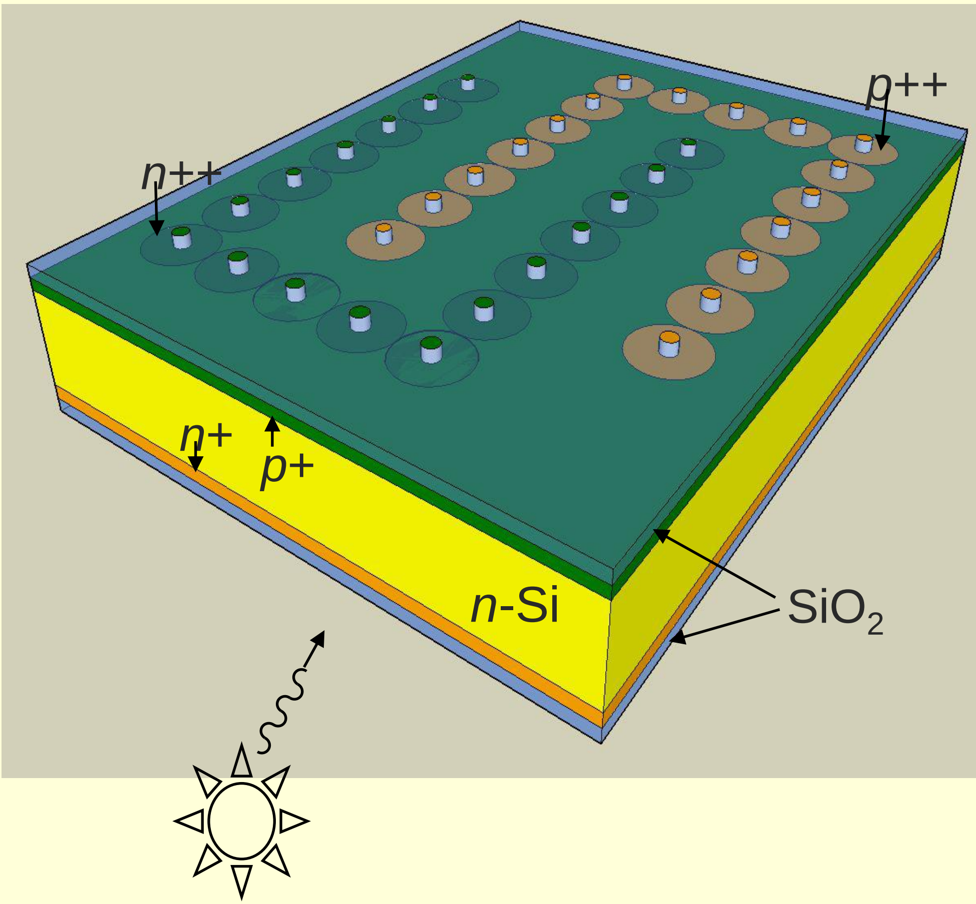
17% Industrial Screen Printed Cell

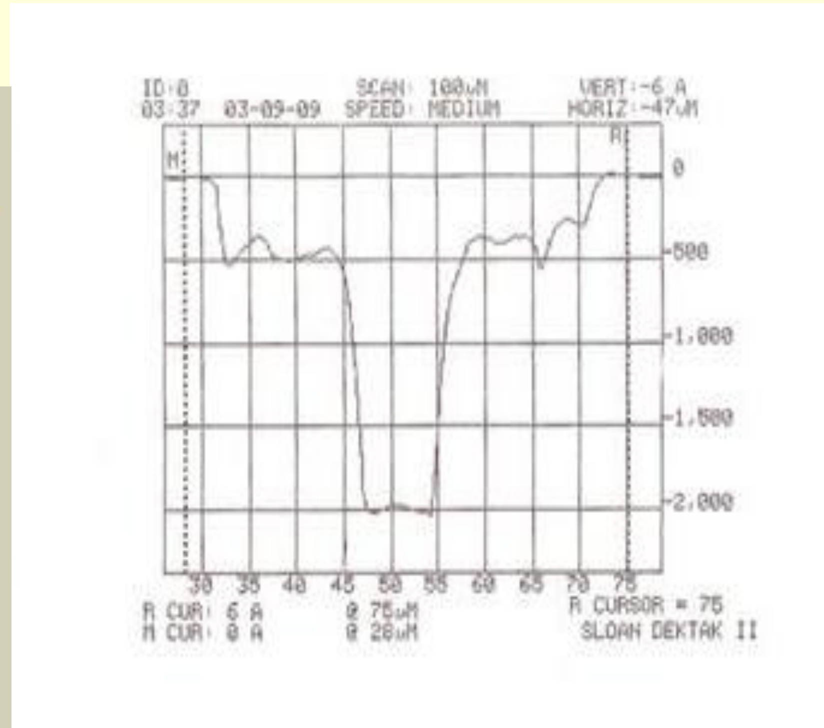


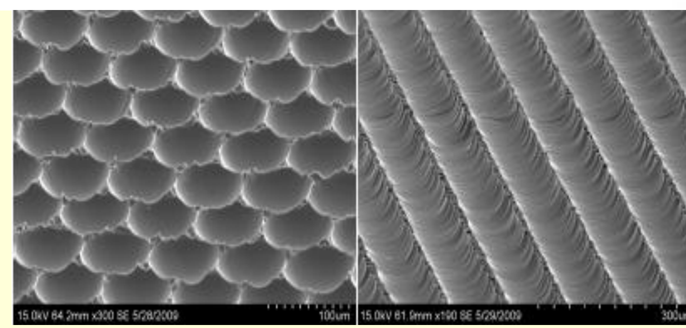
25% Efficient PERL Cell



Inkjet Printing

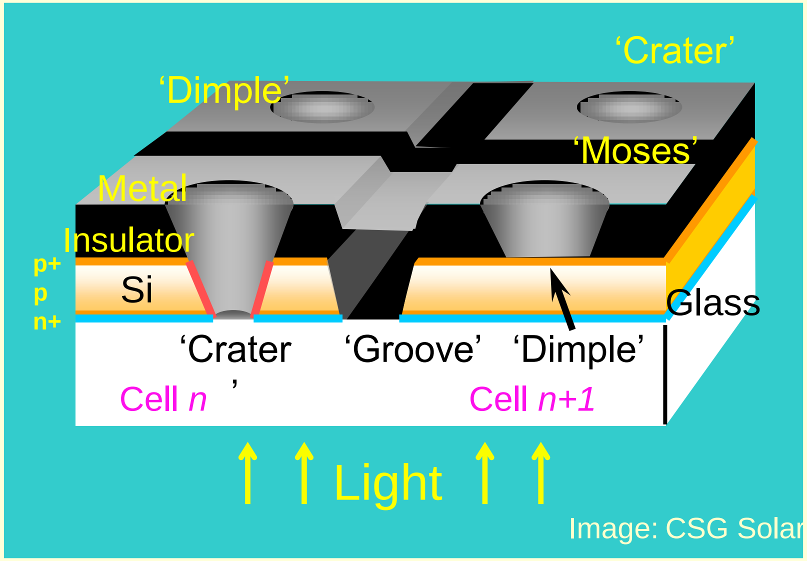


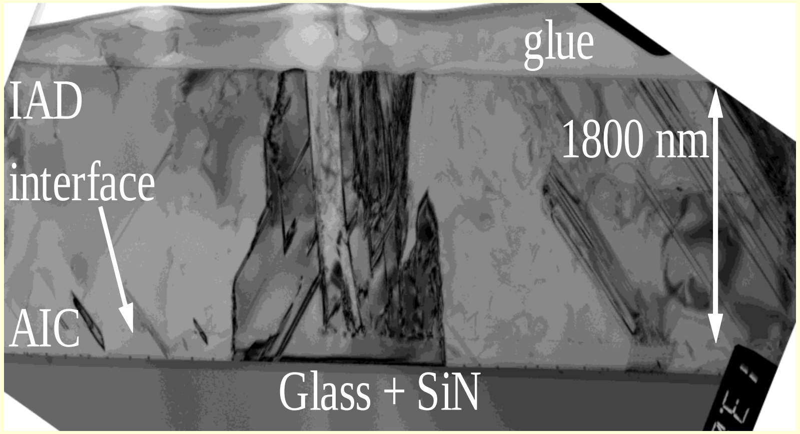




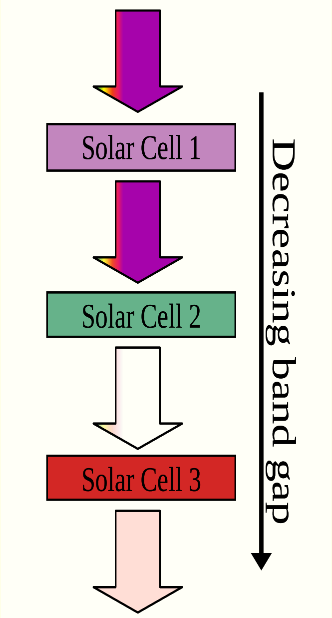
Second Generation (Thin Films) - Si

- Thin films on supporting substrate
  - Amorphous/microcrystalline Si
  - CIGS (In: CRITICAL (US DoE))
  - CdTe (Te: NEAR-CRITICAL (US DoE))
  - Crystalline Si
  - Cu_2ZnSnS_4 (CZTS)
  - Organic PV
- Lower efficiency than wafers but lower cost per m^2
- Large manufacturing unit
- Fully integrated modules
- Aesthetics

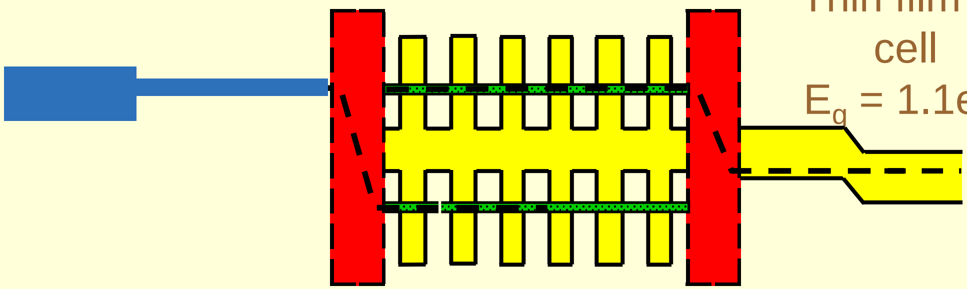


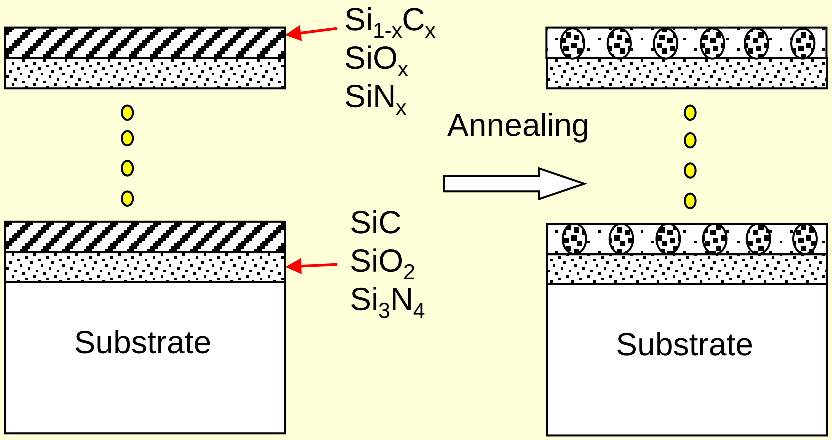


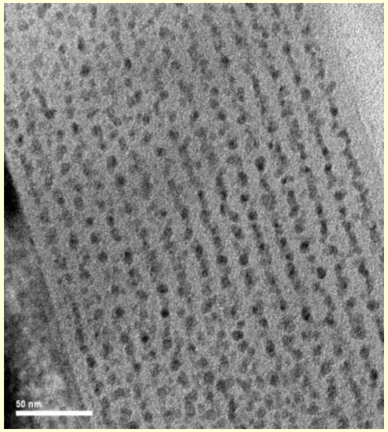
Silicon based Tandem Cell



Engineer a wider band gap – Si QDs



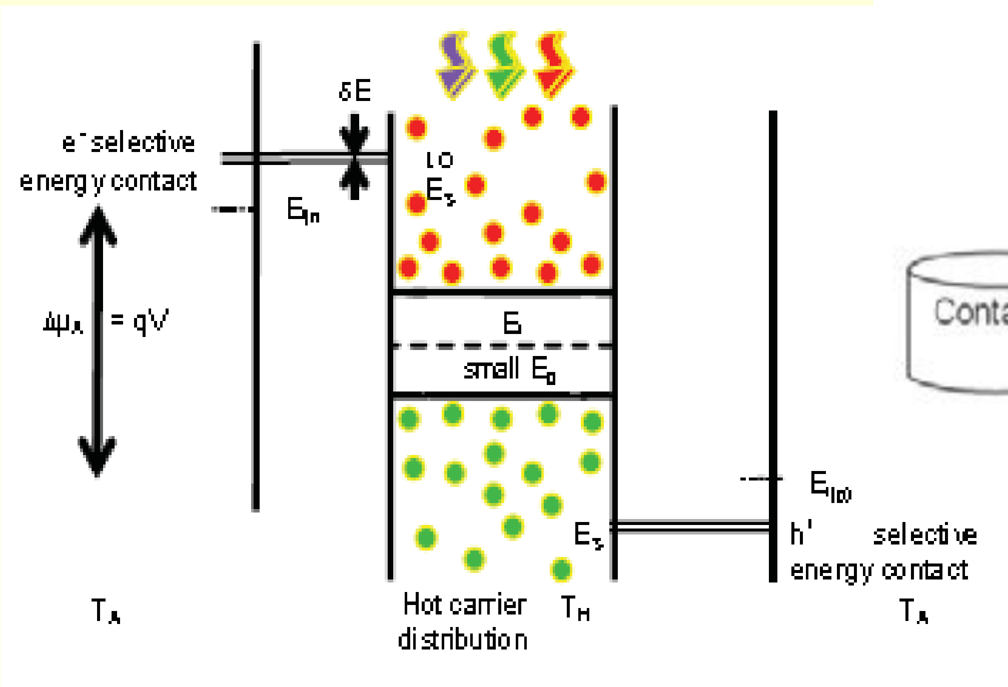


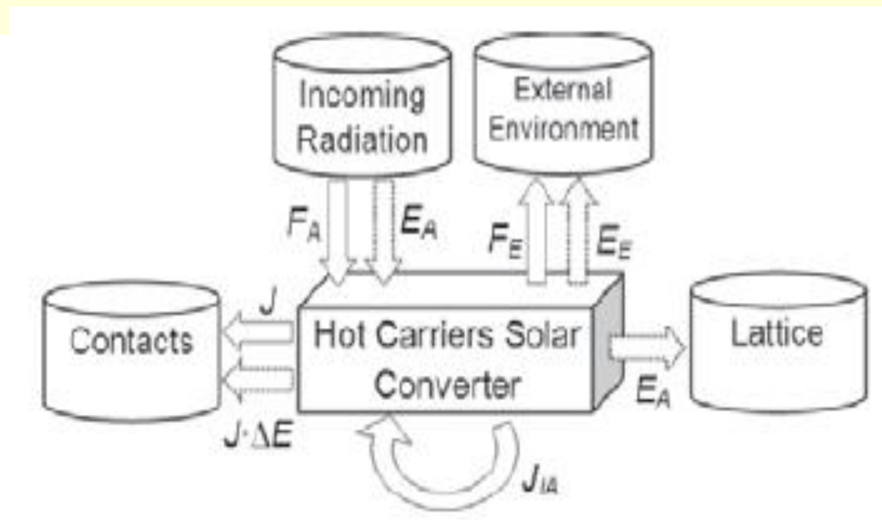


Hot Carrier Cell

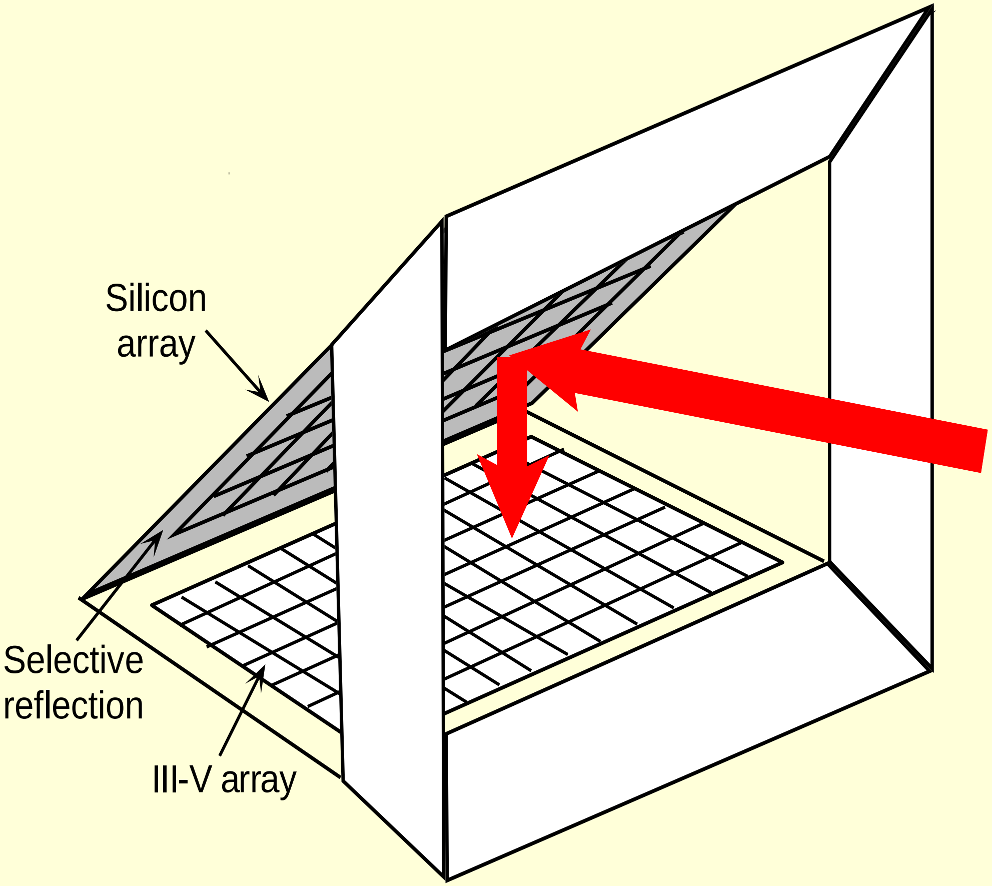
Extract hot carriers before they can thermalise:

1. need to slow carrier cooling
2. need energy selective, thermally insulating contacts

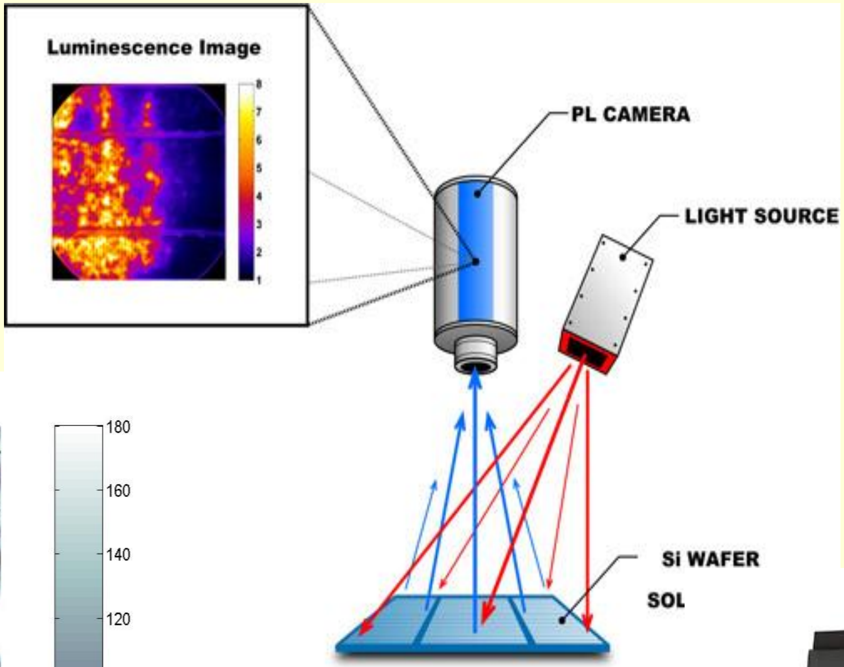


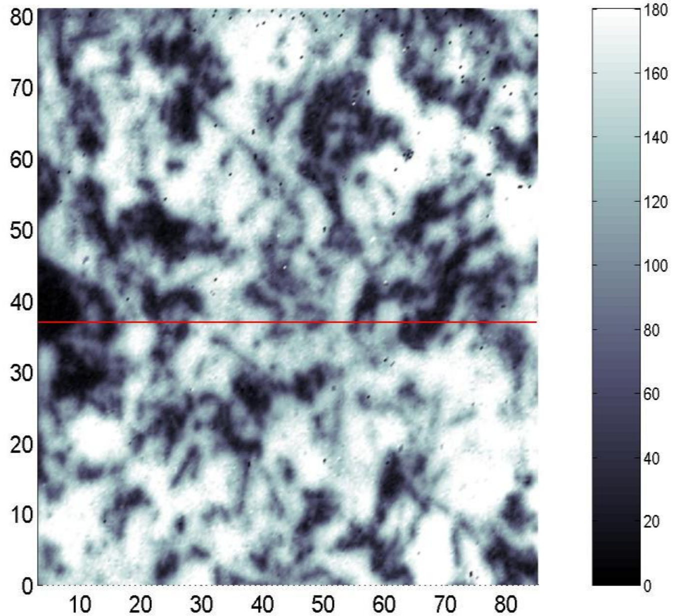


Spectrum Splitting for Concentrating PV



Photoluminescence Imaging





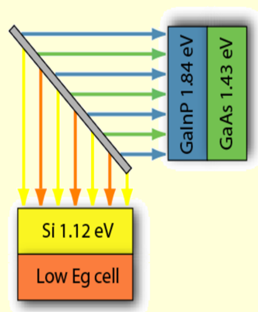
Images courtesy of BT Imaging

High Performance Solar Power

PROJECTS

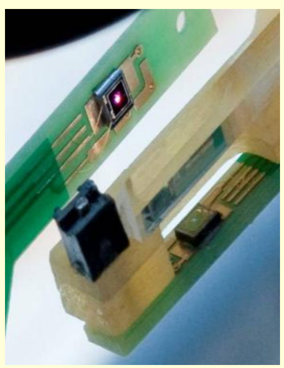
- Ultra-high efficiency solar cells: DARPA VHESC program
- Thin silicon solar cells: collaborative with industry companies
- Advanced concept photovoltaics: collaborative with industry
- Integrated microelectronic sustainable power
- Solar Hydrogen: NSF IGERT

Create innovative concepts for sustainable electricity generation based on rigorous, quantitative, predictive models.

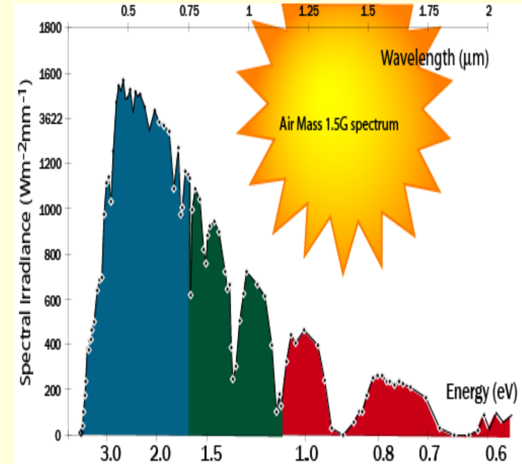


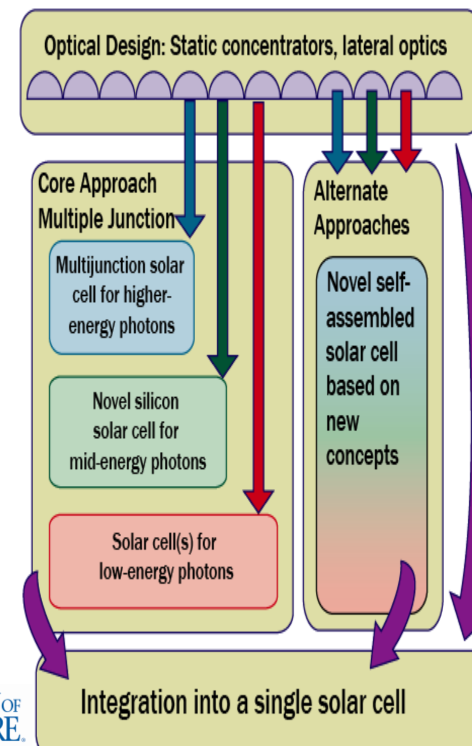
Approach to and results for>50%

We proposed a new integrated optical and electrical solar cell design which allows efficiencies greater than 50%. Our team must invent, develop and transfer to production this new solar cell.



"An efficiency of 36.1% -- was confirmed for this University of Delaware assembly by NREL. This is probably the highest efficiency yet measured for the experimental conversion of sunlight to electricity by any means."





Multiple paths to achieve 50% both in solar cell design and in optical design.
Integrated optical/electrical design provides flexibility.

Approach is to first design for high performance, then to reduce costs.

Ultra-High Efficiency PV Research

Create innovative concepts for sustainable electricity generation based on rigorous, quantitative, predictive models

- Ultra-high efficiency solar cells: Tandem solar cells on silicon leveraging the DARPA VHESC program
- Thin silicon solar cells: collaborative with PV companies
- Advanced concept photovoltaics
- Photovoltaic energy value proposition
- Energy policy

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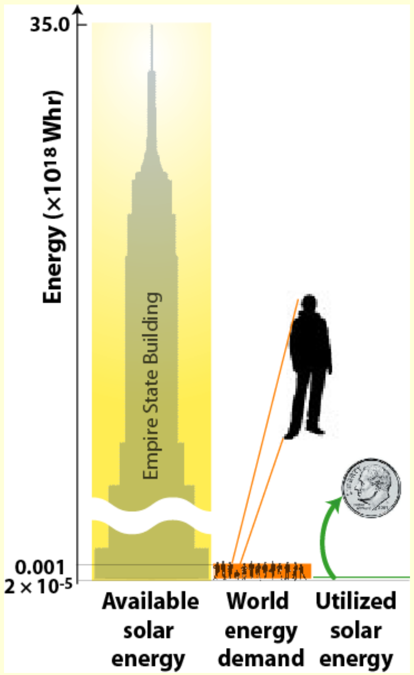
Engineering is the professional art of applying science to the optimum conversion of natural resources to the benefit of man

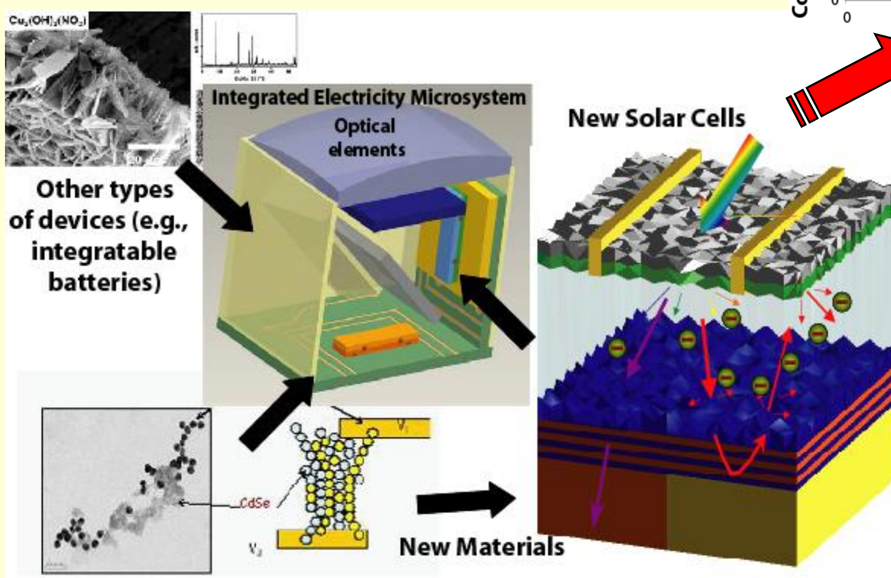
Microsystems Approach

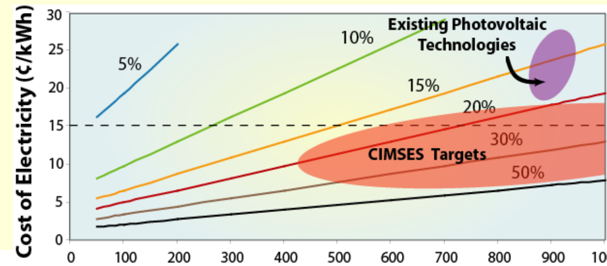
Integration of different concepts and approaches into a single "micro-system" allows transformation in approaches, efficiency, materials, functionality.

Large solar resource, but how to utilize it?



Integrated microelectronic solar cell overcomes existing barriers to high efficiency and low cost

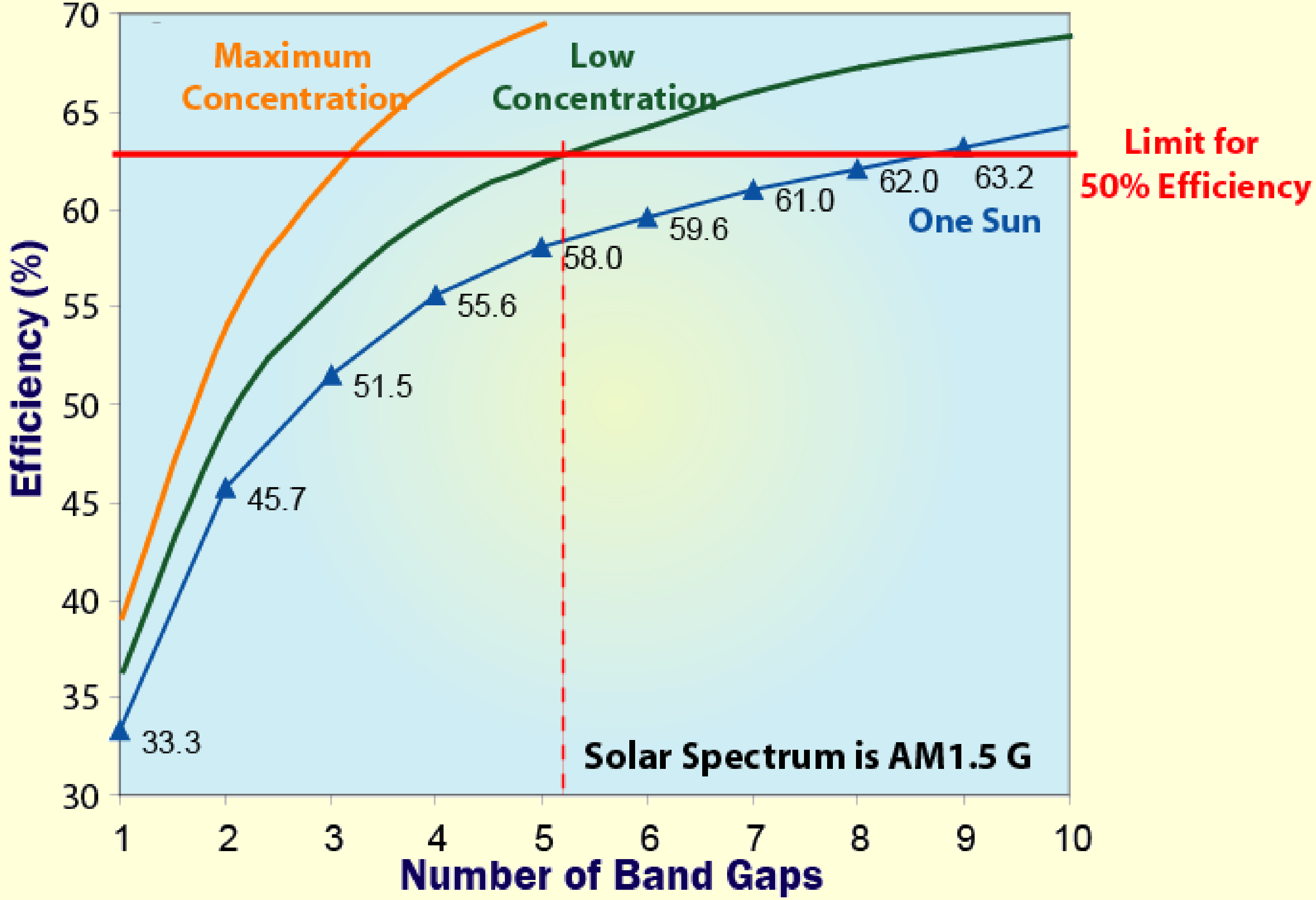




Enables transformative PV applications

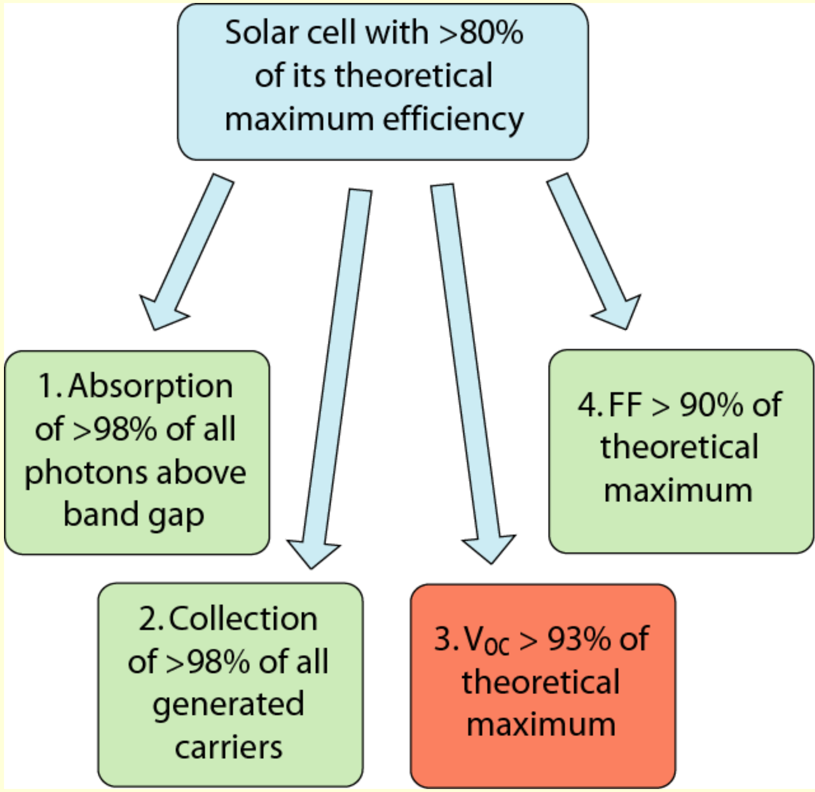
Ultra-high solar cell efficiency

- Concentration & multi-junction architecture



Design rules for high performance

- **For a high solar cell efficiency, simultaneously need high absorption, collection, open circuit voltage and fill factor.**
- **Absorption and collection are typically achievable by “clever” engineering & innovation.**
- **Voltage is controlled by worst, localized region, NOT the same region which absorbs the light – this is fundamentally why single crystal solar cells are highest efficiency.**
- **We will develop models and design rules for all components.**

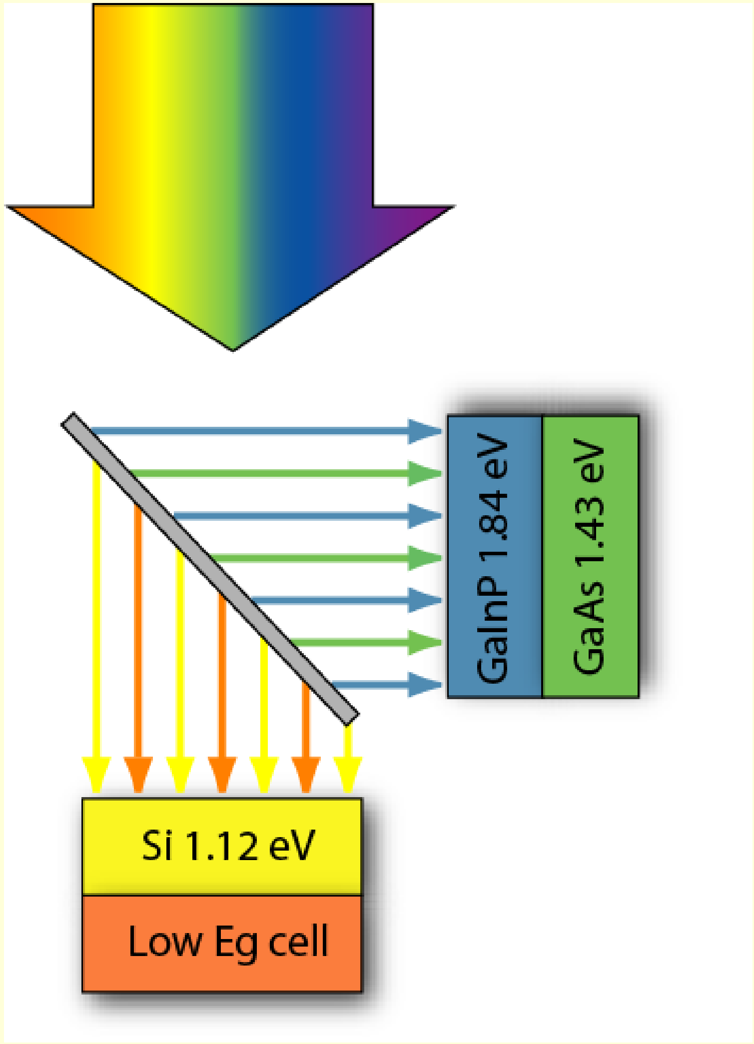


UD to lead $53 million solar cell initiative

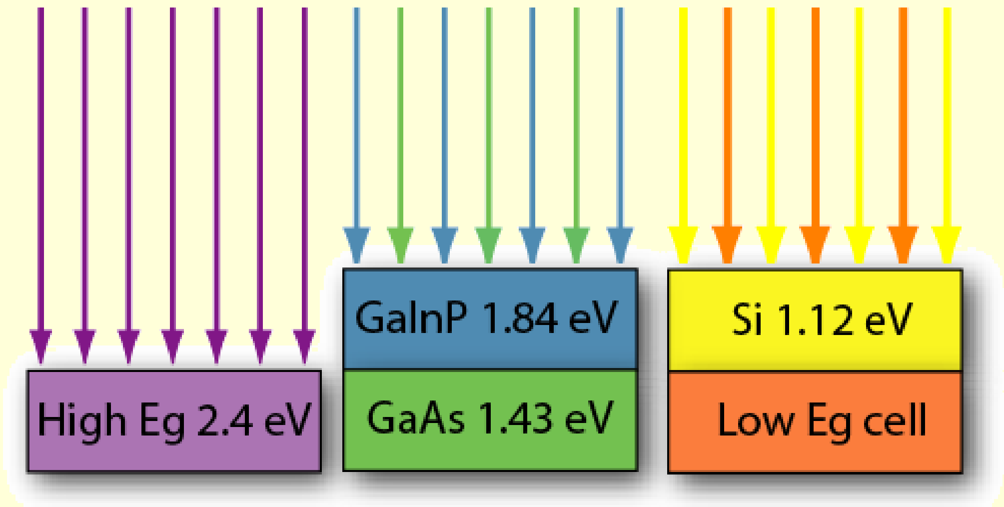
- **4:28 p.m., Nov. 2, 2005—**
- A broad consortium led by the University of Delaware could receive nearly $53 million in funding--with the bulk of the money coming from the Defense Advanced Research Projects Agency (DARPA)--to more than double the efficiency of terrestrial solar cells within the next 50 months.
- The University's Consortium for Very High Efficiency Solar Cells, which consists of 15 universities, corporations and laboratories, could receive up to $33.6 million from DARPA, if all options are awarded, and another $19.3 million from UD and corporate team members.

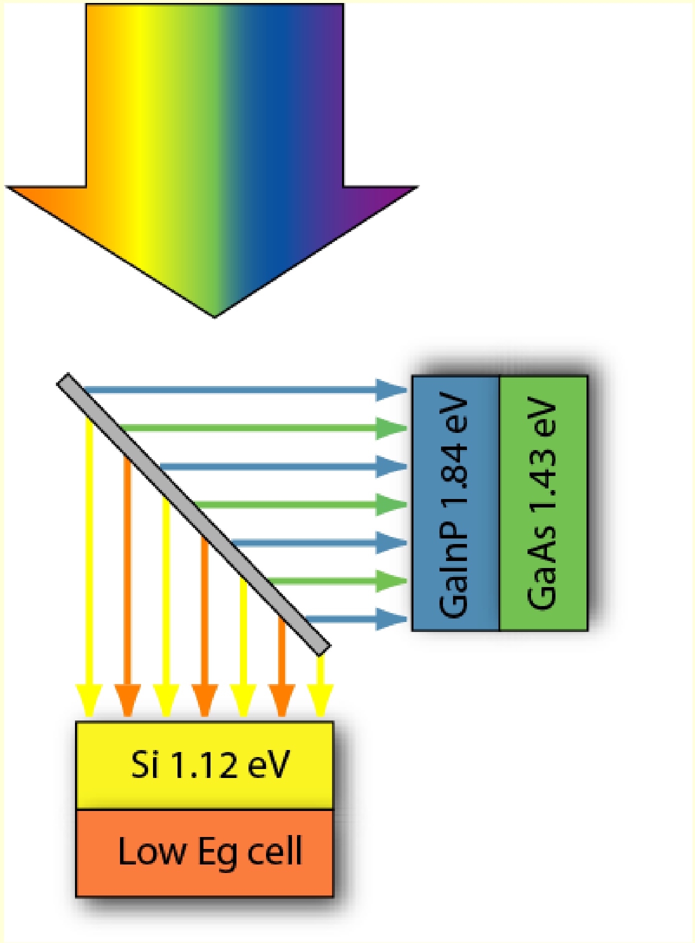
Lateral Design for VHESC

- The Consortium proposes a new integrated optical and electrical solar cell design which allows efficiencies of 56%.
- Our team must invent, develop and transfer to production this new solar cell.

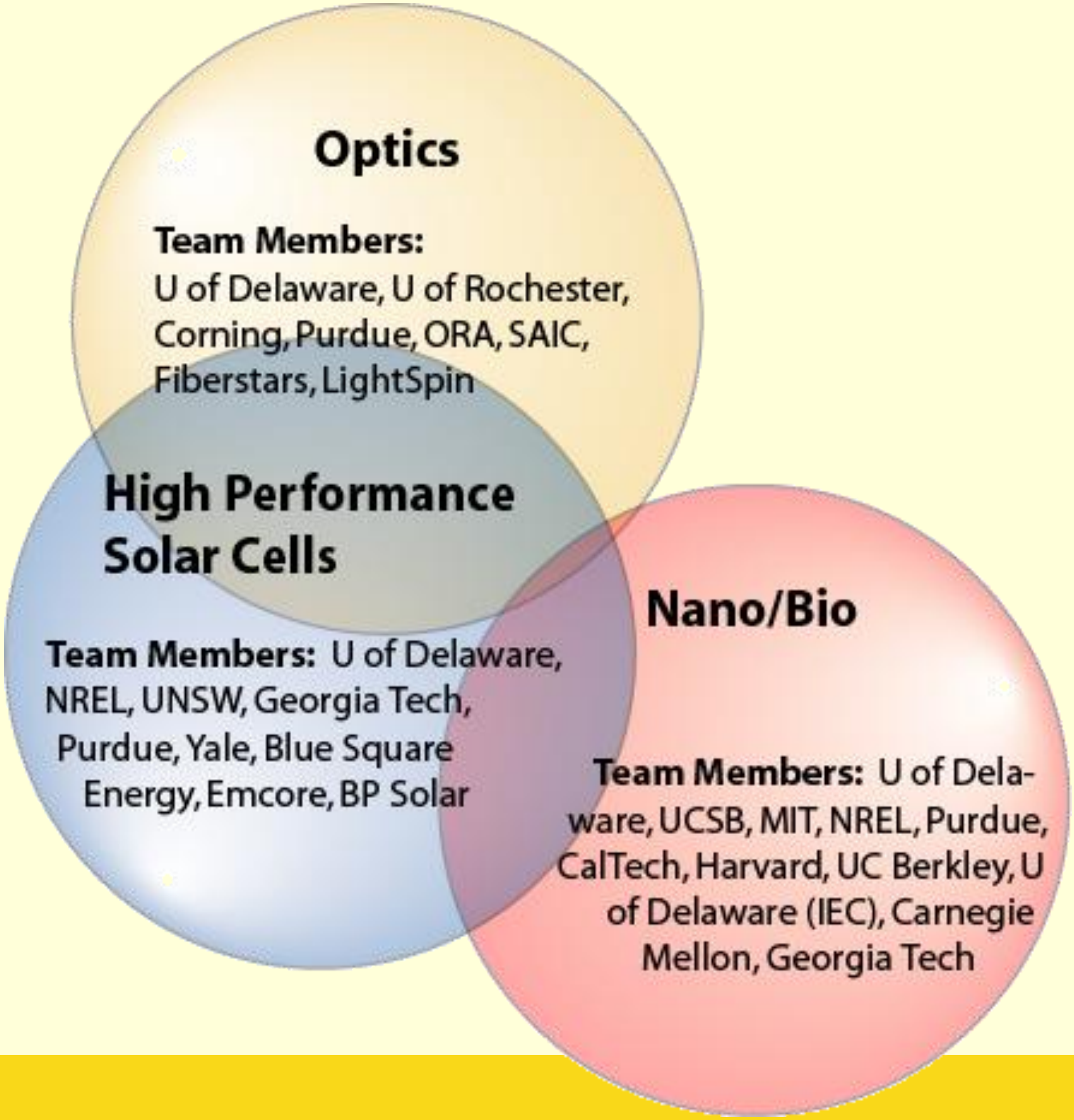


Lateral conceptual designs





Initial Program Organization



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UNIVERSITY OF DELAWARE

6-junction solar cell at 20X & 100X

Analysis of 6-junction solar cell at 20X

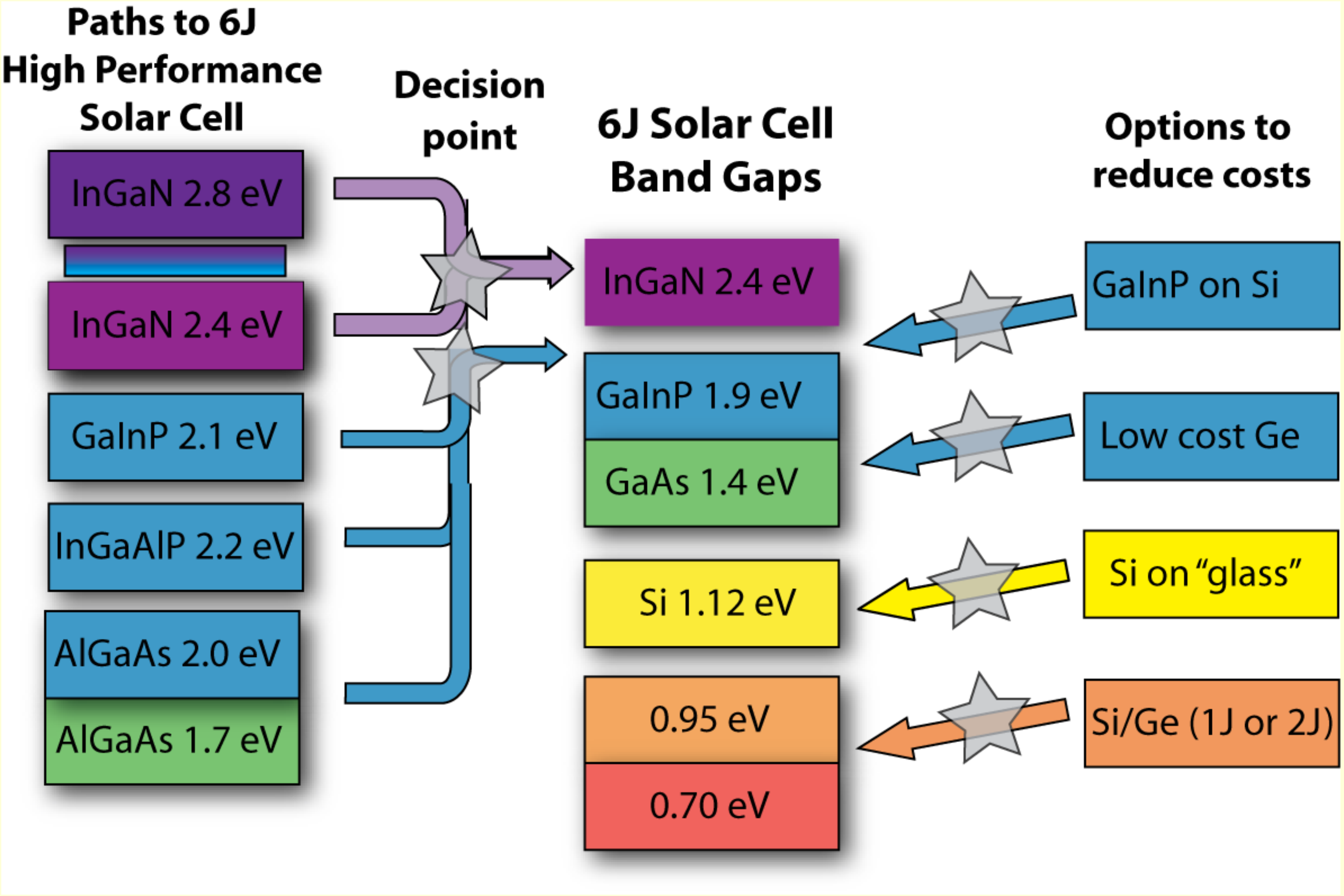
6J Solar Cell Band Gaps	Thermodynamic efficiency	De-rating factor	Ideal target efficiency	100 X Ideal target efficiency
High Eg 2.4 eV	14.9%	0.89	13.8%	13.8%
GaInP 1.84 eV	16.6%	0.86	14.3%	14.3%
GaAs 1.43 eV	13.9%	0.84	11.7%	12.0%
Si 1.12 eV	9.7%	0.80	7.8%	8.5%
0.95 eV	5.0%	0.74	3.8%	4.0%
0.70 eV	4.1%	0.70	2.9%	3.0%
	Total $\eta = 64.2\%$		Total $\eta = 54.3\%$	Total $\eta = 55.6\%$

39.8%

25.4%

6.7%

Paths to high performance, reduced cost



Sum of the solar cell efficiencies

GaInP/GaAs = 31.7%

Silicon (filtered by GaAs) = 5.4%

GaInAsP/GaInAs (filtered by Si) = 5.6%

TOTAL = 42.7%

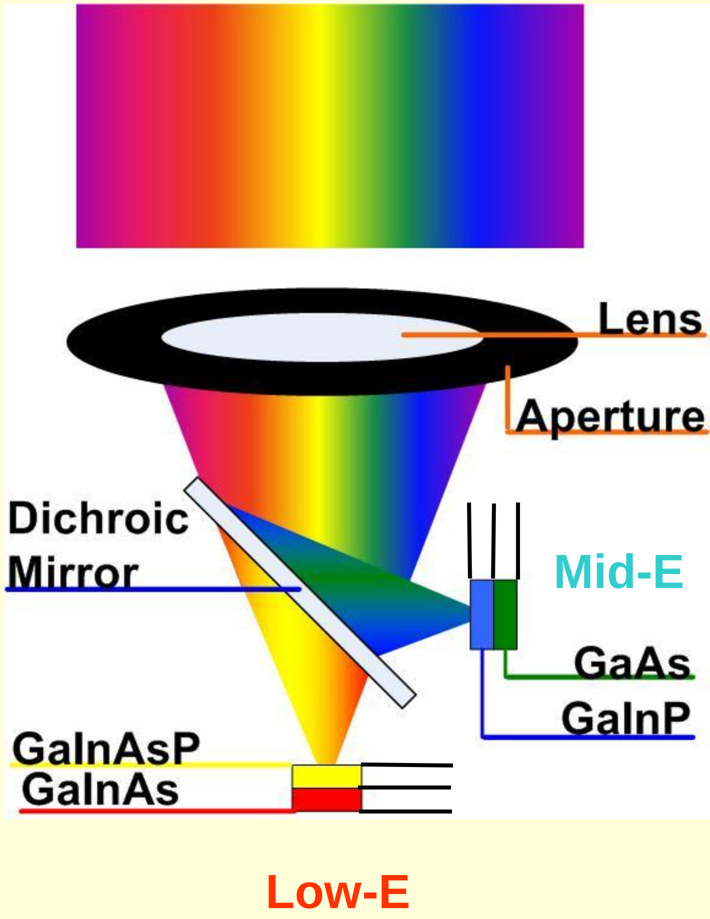
Lateral Spectrum Splitting

- 5 junction design
- Separated contacts
- Sub-module efficiency of 38.5%
  - Transparent high Eg cell desired
  - Low-cost Low Eg solar cell required
- Pathway to high performance, cost-effective approach is described

High Efficiency Lateral Spectrum Splitting CPV

- **Set up a prototype CPV submodule of lateral spectrum splitting structure incorporating:**
  - ✓ **1 concentrator**
  - ✓ **1 dichroic mirror**
  - ✓ **2 tandem solar cells (each has 2 sub-cells)**

30.48X	Solar cell Eff (%)	Lens Eff (%)	Mirror Eff (%)	Optics Eff (%)	Sub module Eff (%)
M-E					
TOP	19.3	93.5	97.2	90.9	17.5
BOT	13.5	93.5	93.5	87.5	11.8
L-E					
TOP	8.9	92.0	97.6	89.8	8.0
BOT	2.6	91.0	93.0	84.6	2.2
Sum	**44.3**	93.0	95.8	**89.1**	**39.5**



Solar cell efficiency tables (version 35)

"An efficiency of 36.1% -- was confirmed for this University of Delaware assembly by NREL. This is probably the highest efficiency yet measured for the experimental conversion of sunlight to electricity by any means."

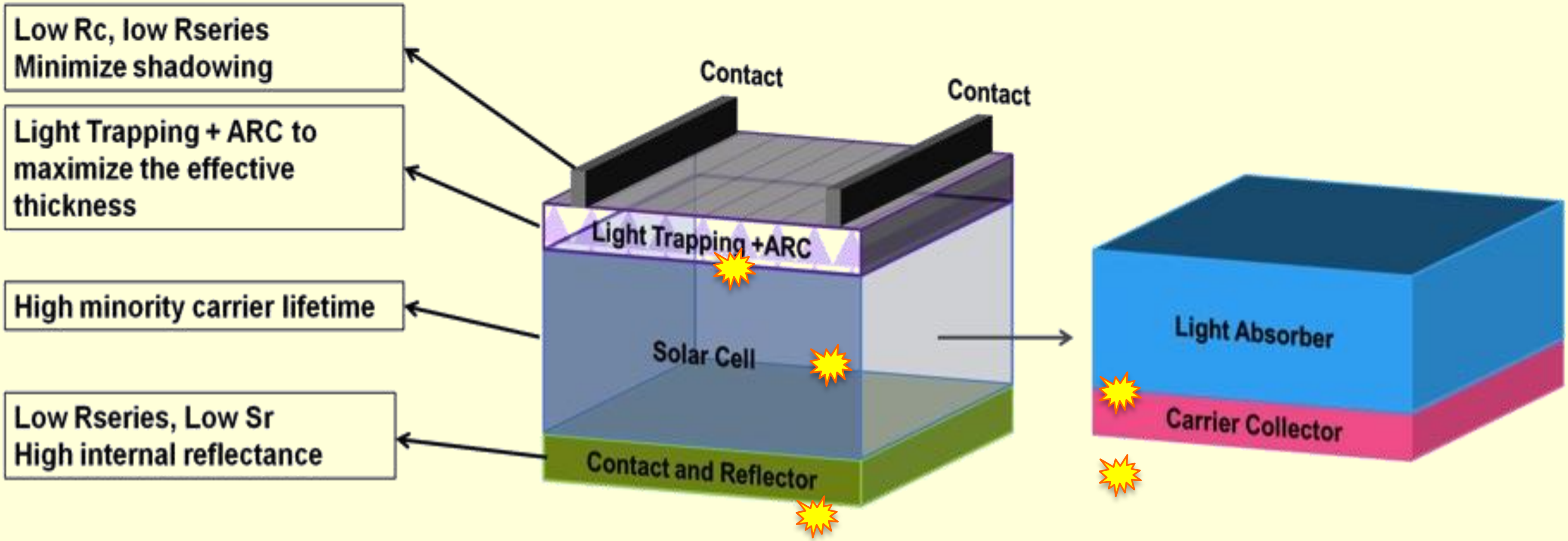
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2010; 18:144–150

Martin A. Green1, Keith Emery2, Yoshihiro Hishikawa3 and Wilhelm Warta4
1 University of New South Wales, 2 National Renewable Energy Laboratory, 3 National Institute of Advanced Industrial Science and Technology (AIST), 4 Fraunhofer Institute for Solar Energy Systems

Voltage, Current Increases

- High performance thin Si solar cell **design**.
- Increase voltage: reduced junction area
- Increase current: metallic reflector
- **Fabrication** and improvement
- **Analysis** of initial results
- Pathway to high performance thin Si solar cell

First Voltage, Second Current



High bulk lifetime / reduced bulk recombination → High Open Circuit Voltage → High Efficiency

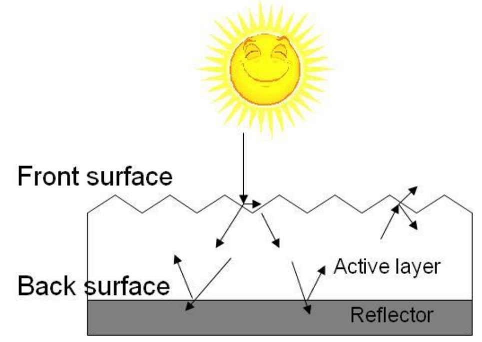
- Epitaxial c-Si
- Thin absorber

- Surface passivation

- Light Trapping
- Back reflector

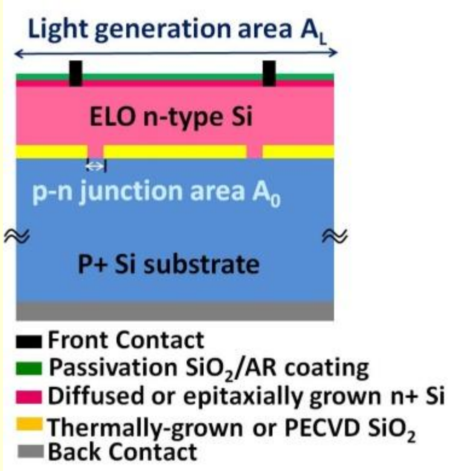
Thin Silicon Solar Cells

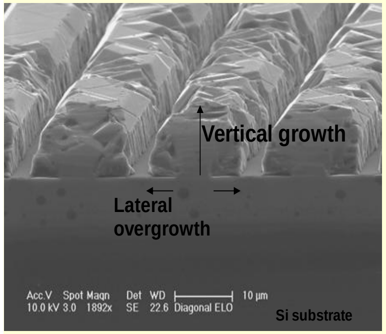
Thin Silicon Solar Cells

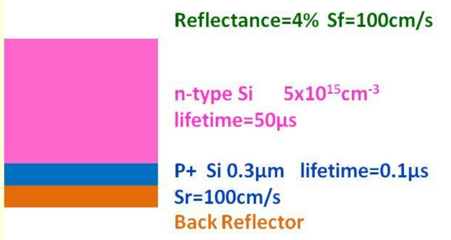


Design, Fabrication and Analysis of High Efficiency Thin Silicon Solar Cells Based on Epitaxial n-Si Absorber

N-type Si has the advantages of longer lifetime, the surfaces being easier to passivate, no light-induced degradation and being less affected by metal contamination.







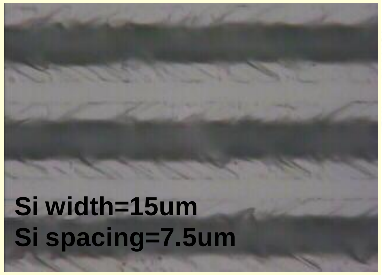
High Open Circuit Voltage

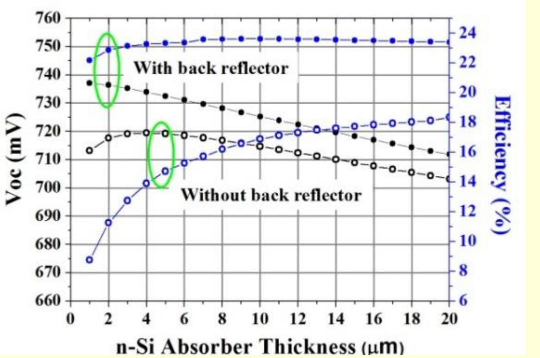
- Reduced bulk recombination volume
- Low front and back surface recombination

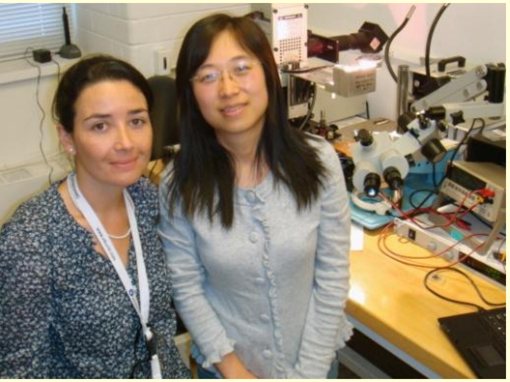
High efficiency requires

- Good light trapping

$$Voc = \frac{kT}{q}\ln\left(\frac{A_L J_L}{A_0 J_0}+1\right)$$







We proposed a new epitaxial lateral overgrowth structure which has a smaller p-n junction area (A_0) than the light generation area (A_L). By lowering the dark saturation current, higher Voc is expected. If A_L is ten times of A_0, the gain of Voc is 59.4mV.

PC1D simulation for Voc and efficiency as a function of n-Si absorber thickness (The blue curves are for efficiency and black curves for Voc)

Ruiying Hao, C. Paola Murcia, AmberWave Inc.

UNSW THE UNIVERSITY OF NEW SOUTH WALES

Solar Power Program

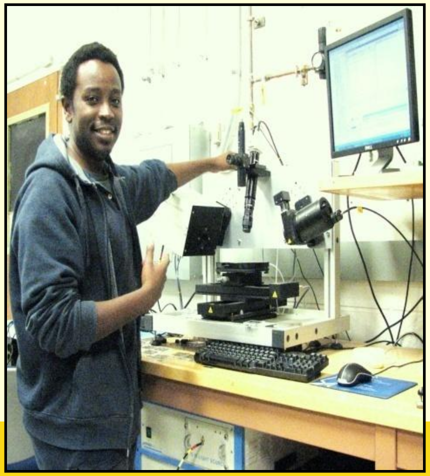
Thin Silicon Solar Cells Group

Increasing the Jsc of Thin Silicon Solar Cells

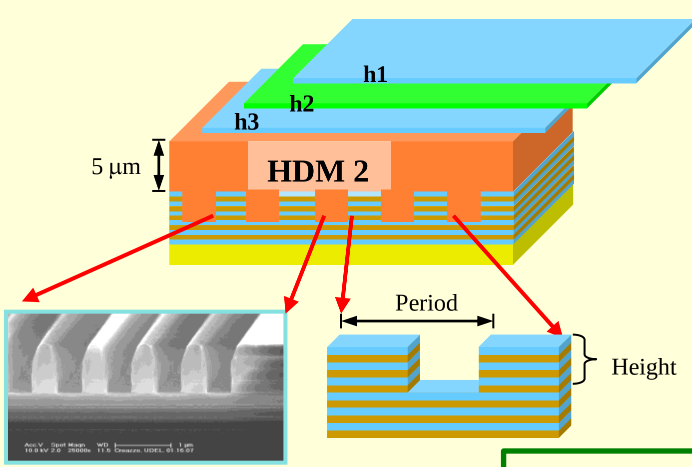
Using:

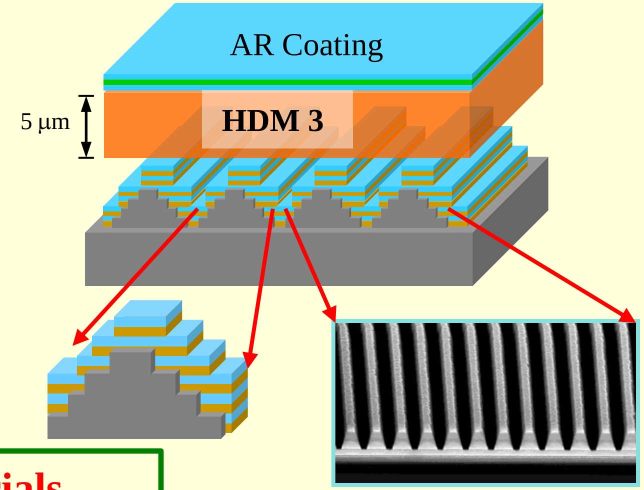
1. AR Coatings
2. Nano-Texturing
3. Photonic Crystals
4. Diffraction Gratings

James G. Mutitu



HDM Structures Combine DBR Structures with Metallic Reflectors

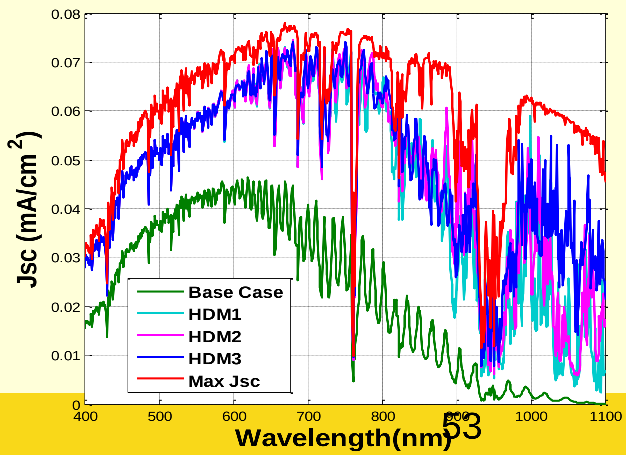




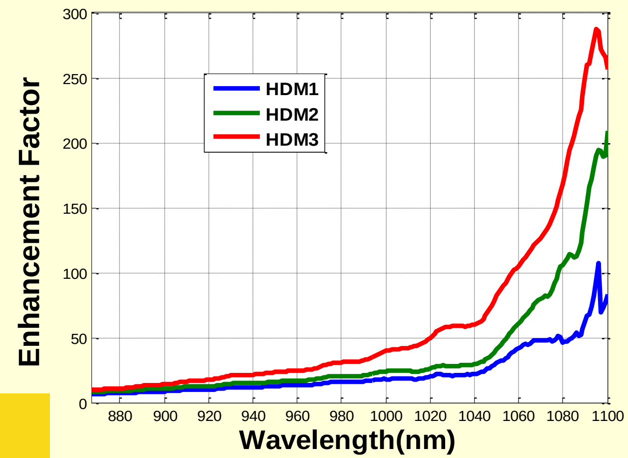
Materials

SiO_2	c-Si
Si_3N_4	a-Si
Metal	

Jsc

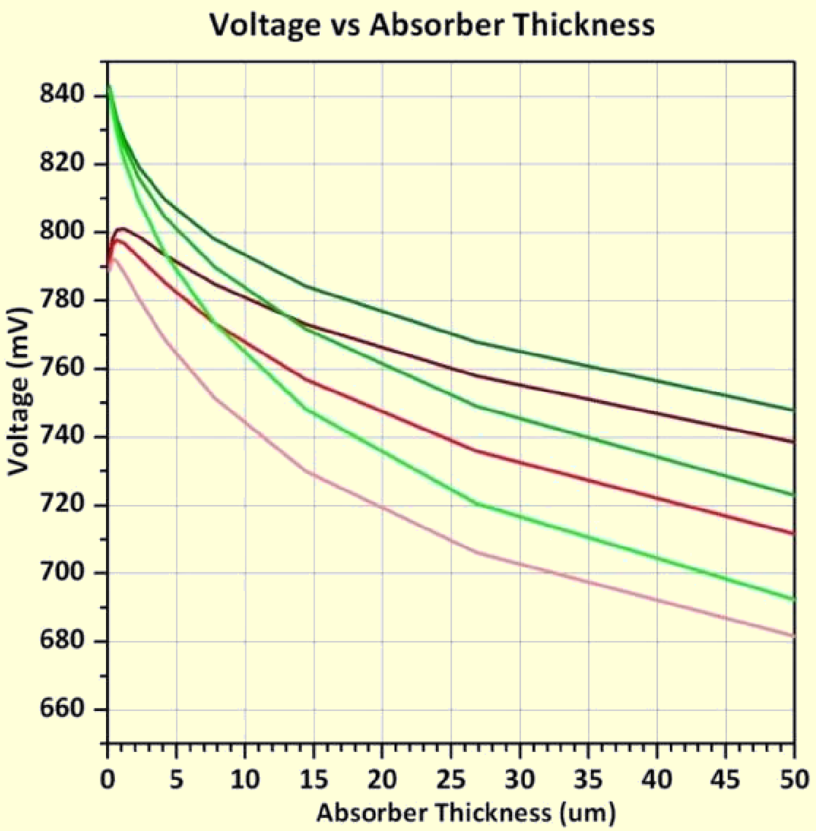


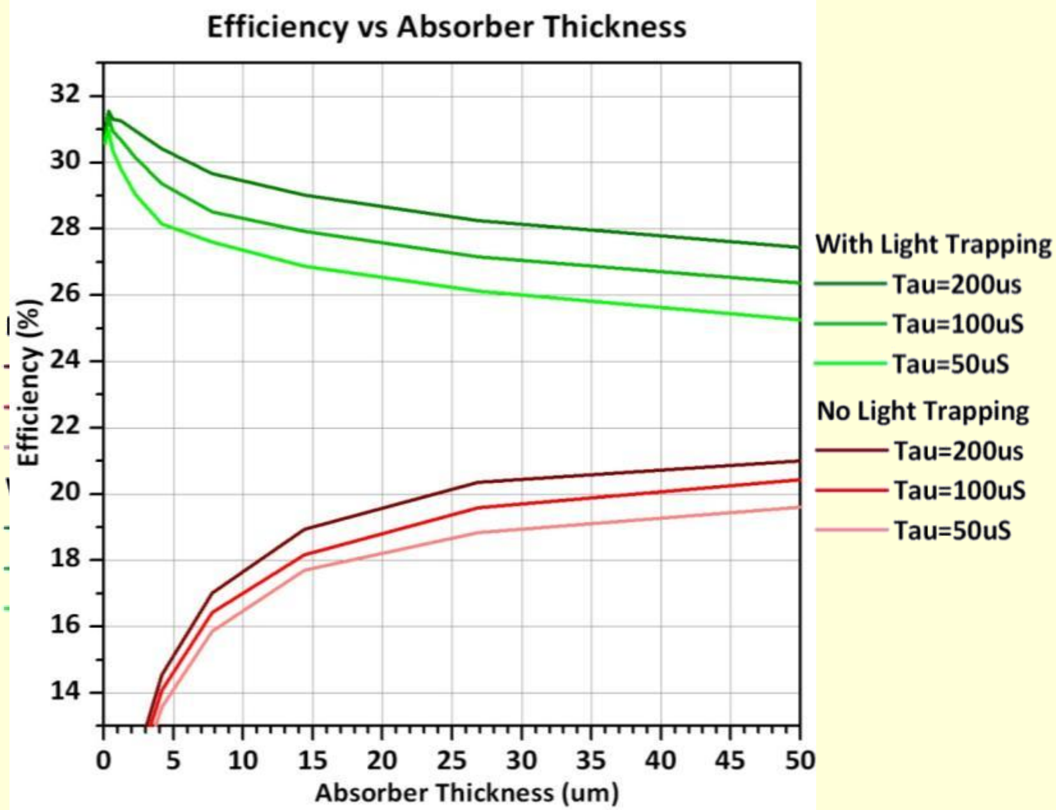
Enhancement Factor



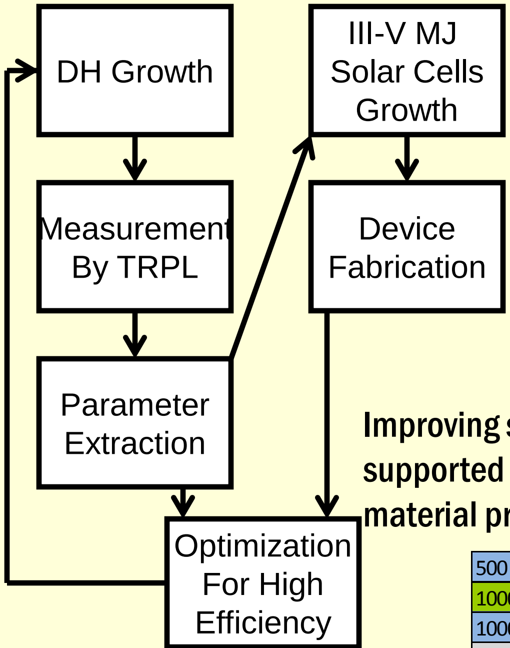
Voltage and efficiency vs thickness &lifetime

Light trapping is not necessary to demonstrate high voltage





III-V Group



Utilize direct optical technique to independently resolve surface and bulk lifetime for rigorous, quantitative, predictive models and improved designs

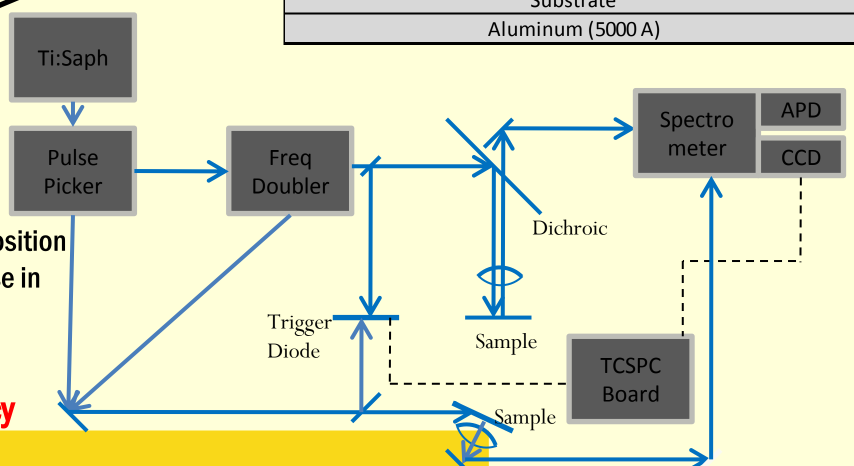
Individual layers will be modeled as a function of lifetime parameter extraction results for full solar cell structure. Results will be compared to multijunction devices fabricated and will determine the extent that TRPL can be used to evaluate solar device performance

	Gold (1000 A)
	Germanium (200 A)
	Palladium (100 A)
250 A	Si/Te:In(.01)Ga(.99)As
5000A	Si:In(.01)Ga(.99)As
500 A	Window Layer
1000 A	Te:In(.5)Ga(.5)P
100 A	NID:In(.5)Ga(.5)P
3 um	Zn:In(.5)Ga(.5)P
1000 A	Back Surface Field
200 A	C:Al(0.3)Ga(0.7)As
200 A	Te:GaAs
500 A	Window Layer
1000 A	Te:In(.01)Ga(.99)As
100 A	NID:In(.01)Ga(.99)As
3 um	Zn:In(.01)Ga(.99)As
1000 A	Back Surface Field
2 um	In(.01)Ga(.99)As
185 A	In(0.5)Ga(0.5)P
	Substrate
	Aluminum (5000 A)

Improving solar cells grown in Veeco K475 As/P MOCVD Reactor supported by device results and analysis plus fundamental material properties based on time-resolved photoluminescence

500 A	Window Layer
1000 A	Te:In(.01)Ga(.99)As
1000 A	Back Surface Field
	Substrate

500 A	Window Layer
3 um	Zn:In(.01)Ga(.99)As
1000 A	Back Surface Field
	Substrate



Lifetime analysis by TRPL of double heterostructures to optimize material composition and growth as well as interface quality for use in high-efficiency multijunction solar cells

Approach is to first design for high performance, then analyze efficiency trade-offs with lower cost materials

Lateral Spectrum Splitting PV Group

PROJECTS

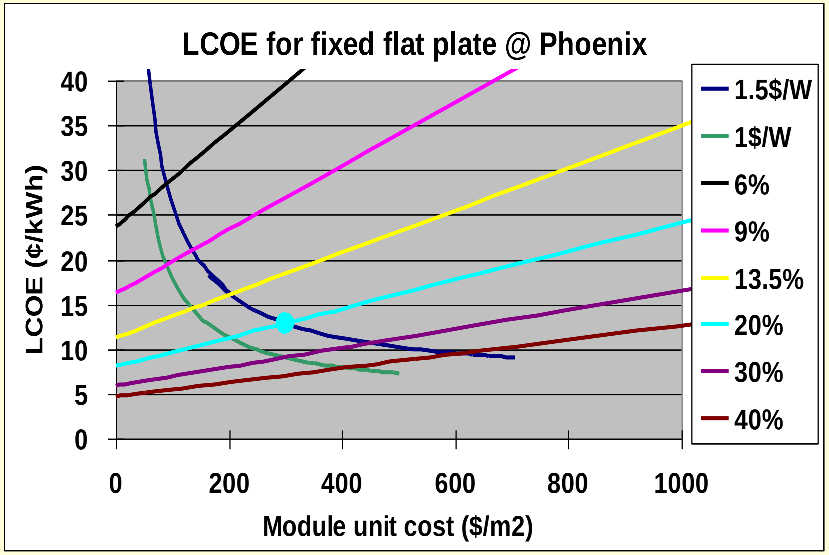
The value of PV module efficiency

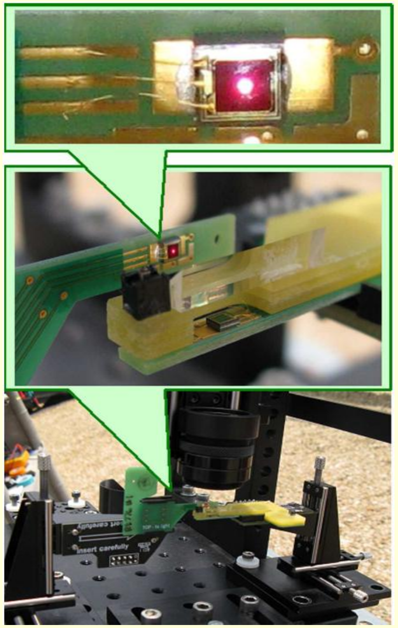
Design rules of CPV modules

Measurement of Lateral Spectrum Splitting CPV (LSSCPV) sub-modules

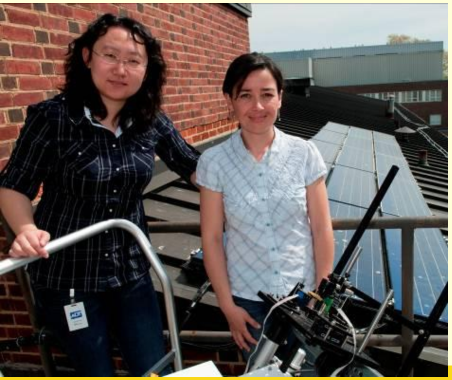
Variation designs of LSSCPV sub-modules

New module designs containing CPV and planar PV





The value of "test bed" concept is the assessment of the component efficiency, which helps locate the problems of current sub-modules and identify approaches to higher sub-module efficiency.



In a PV system, the area-related cost and the fixed cost determines the value of the module efficiency. To achieve a certain Levelized Cost of Energy (LCOE), the module efficiency must be maintained above a certain value no matter how low the module cost can be.

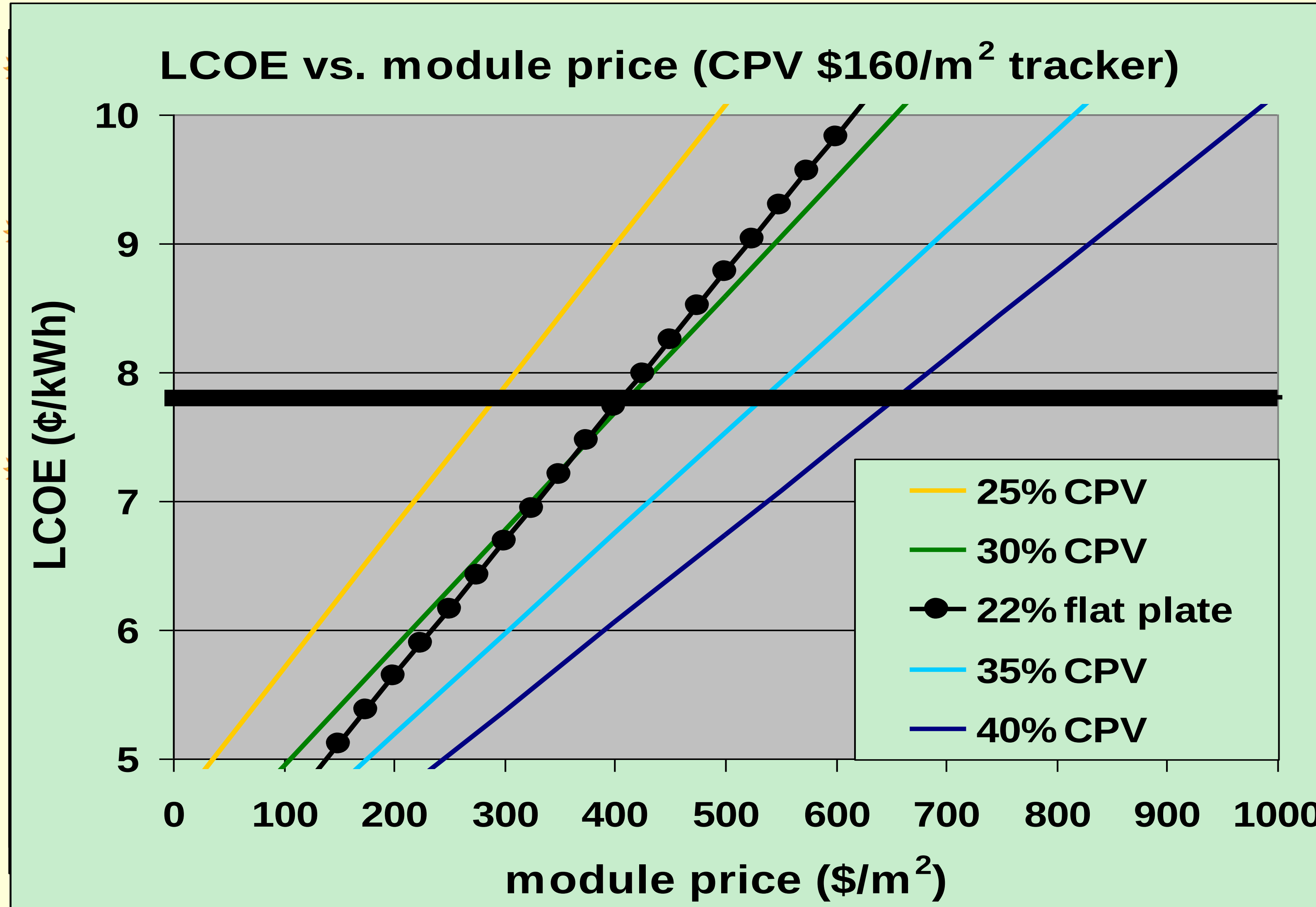
"An efficiency of 36.1% based on a 0.31 cm2 aperture area was confirmed for this University of Delaware assembly by NREL. This is probably the highest efficiency yet measured for the experimental conversion of sunlight to electricity by any means."

--Solar cell efficiency tables (version 35) 2010, PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS

Value of PV Module Efficiency and Current Status

- Value of module efficiency in lowering PV system levelized cost of energy (LCOE)
- Efficiency losses in traditional high-X CPV
- Lateral spectrum splitting: an approach to high module efficiency
- Energy production comparison across different PV configurations

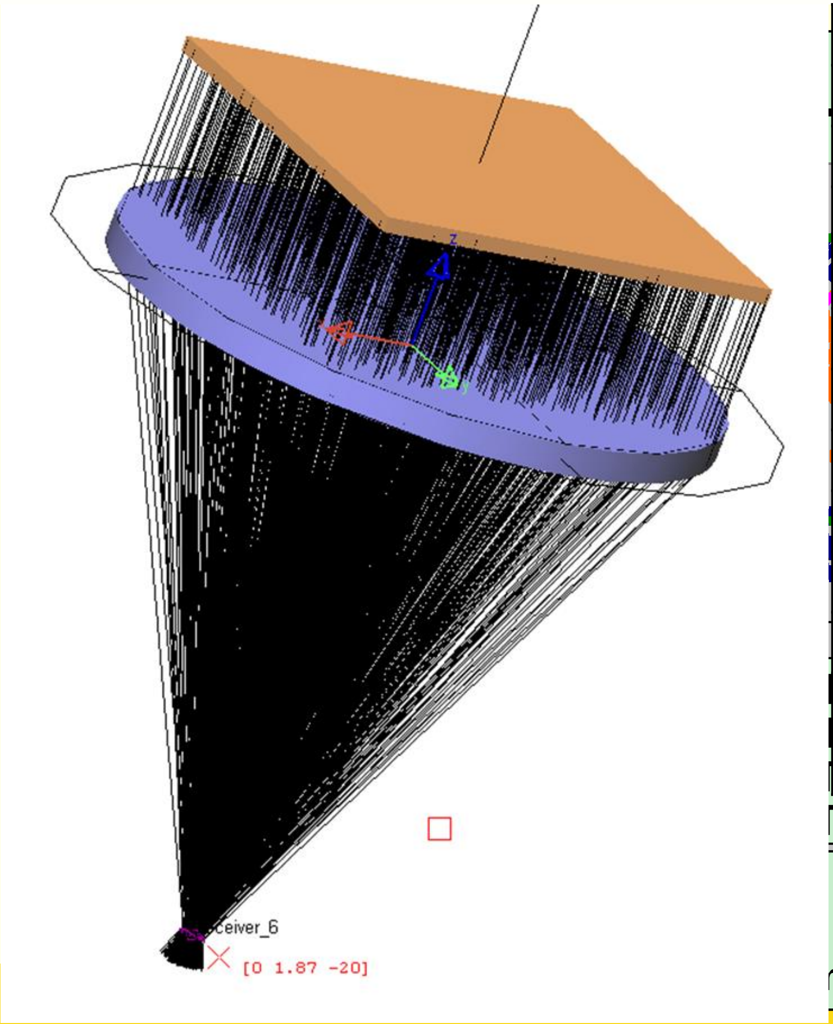
Value of PV Module Efficiency: Lower LCOE



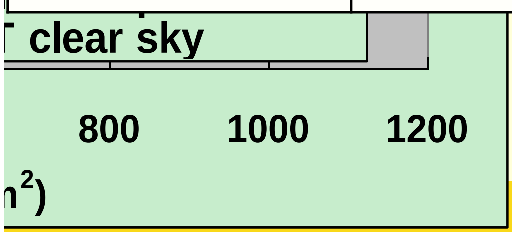
- CPV needs module efficiency higher than 30% to be competitive!

High-X CPV with monolithic cells: Loss Analyses

- Optics: sensitive to pointing error under high-X concentration.



	Local Loss	Integrated Efficiency
Incident		**100.0%**
Reflection top	**3.9%**	**96.1%**
Reflection bottom	**5.1%**	**91.3%**
5um radius	**2.7%**	**88.8%**
3 degree draft	**2.3%**	**86.8%**
Uncaptured light at different pointing errors (°)		
0.0	**3.0%**	**84.2%**
0.1	**3.3%**	**83.9%**
0.2	**5.1%**	**82.3%**
0.3	**7.6%**	**80.1%**
0.4	**11.7%**	**76.7%**
0.5	**17.6%**	**71.5%**



PV Energy Production

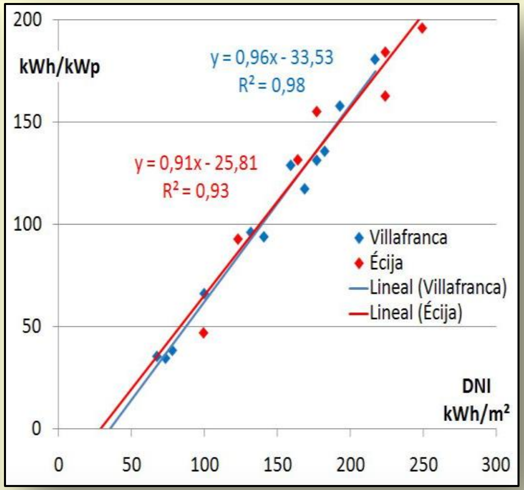
Studied systems

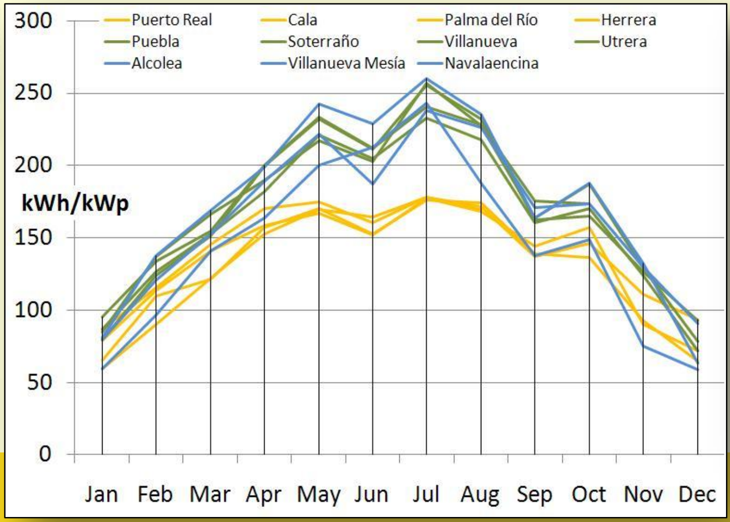
- Fixed flat plate
- 1-axis tracking flat plate
- 2-axis tracking flat plate

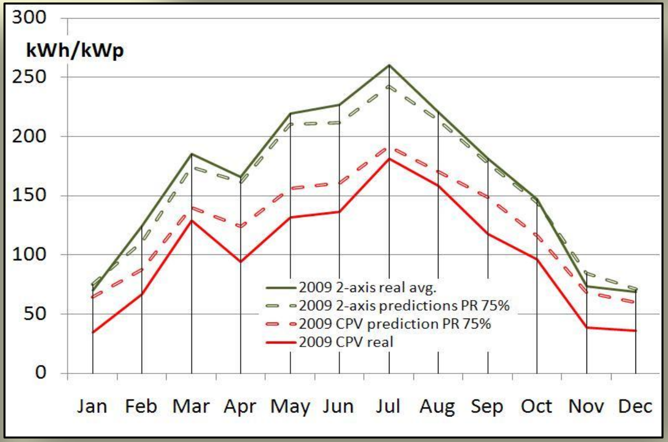
Analysis of *Energy Production* by different systems

Results

- 1 and 2-axis sun tracking *Energy Production* increment from fixed is under 70% of expected
- CPV *Energy Production* under expected
- CPV model for *Energy Production* prediction
- CPV silicon and multijunction comparison
- CPV silicon temperature dependence model







UNIVERSITY OF DELAWARE

United States – Australia Solar Energy Collaboration (USASEC) Special Research Initiative (SRI)

The Australian Solar Institute (ASI) is interested in receiving feedback from the Australian solar Research community in relation to a proposed Strategic Research initiative (SRI) funded initially under the auspices of the United States Australia Solar Energy Collaboration (USASEC).

Objectives

The objectives of an SRI would include to:

- provide a degree of funding stability, and by extension employment security, to leading research teams that, subject to regular performance and program reviews, ensures they can focus on delivering the required research outcomes;
- provide a framework for Australia's leading researchers to stay closely aligned to industry and market requirements;

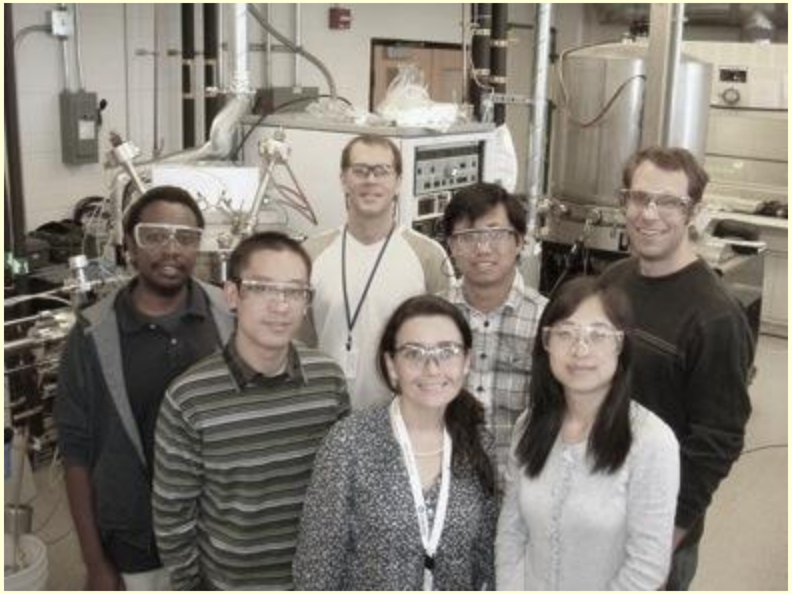
maximise leverage from international collaboration to minimise duplication of effort, maximise utilisation of high value overseas laboratories and focus on specific areas where Australian researchers can add unique value.

Fall 2009

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Summer 2011

Acknowledgement



ACKNOWLEDGEMENT

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Thank you!