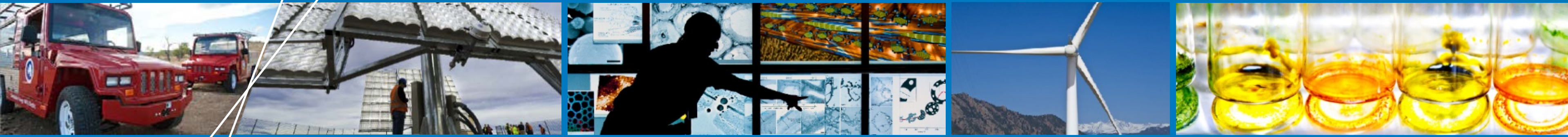
High-Efficiency Tandem Absorbers for Economical Solar Hydrogen Production



2015 U.S. DOE Hydrogen & Fuel Cells Program Review

Todd G. Deutsch

June 11th, 2015

Project ID: PD115

Overview

Timeline and Budget

- **Project start date: 10/1/14**
- **Project end date: 9/30/17**
- **Total project budget: $3M**
  - Total recipient share: $0
  - Total federal share: $3M
  - Total DOE funds spent*: $0.5M**

* As of 3/31/15

** Includes UNLV, LLNL, LANL, UH support

Barriers

- **Barriers addressed**
  - AE. Materials Efficiency –Bulk and interface.
  - AF. Materials Durability – Bulk and interface
  - AG. Integrated Device Configurations

Partners

- **Interactions/collaborations**
  - University of Nevada Las Vegas
  - Lawrence Livermore National Lab
  - University of Hawaii
  - Los Alamos National Laboratory
  - Stanford University
  - Colorado School of Mines
  - University of Colorado-Boulder
  - University of Louisville
  - University of Oregon
  - Denmark Technical University

Relevance

Objectives

- Long-Term: Develop highly-efficient, durable material that can operate under 10-15x (or higher) solar concentration and generate renewable hydrogen for <\$2/kg from photoelectrochemical (PEC) water splitting
- Current year:
    - Push boundaries on achievable semiconductor photoelectrochemical solar-to-hydrogen (STH) efficiencies
    - Continue development of stabilizing surface modifications viable at high current densities

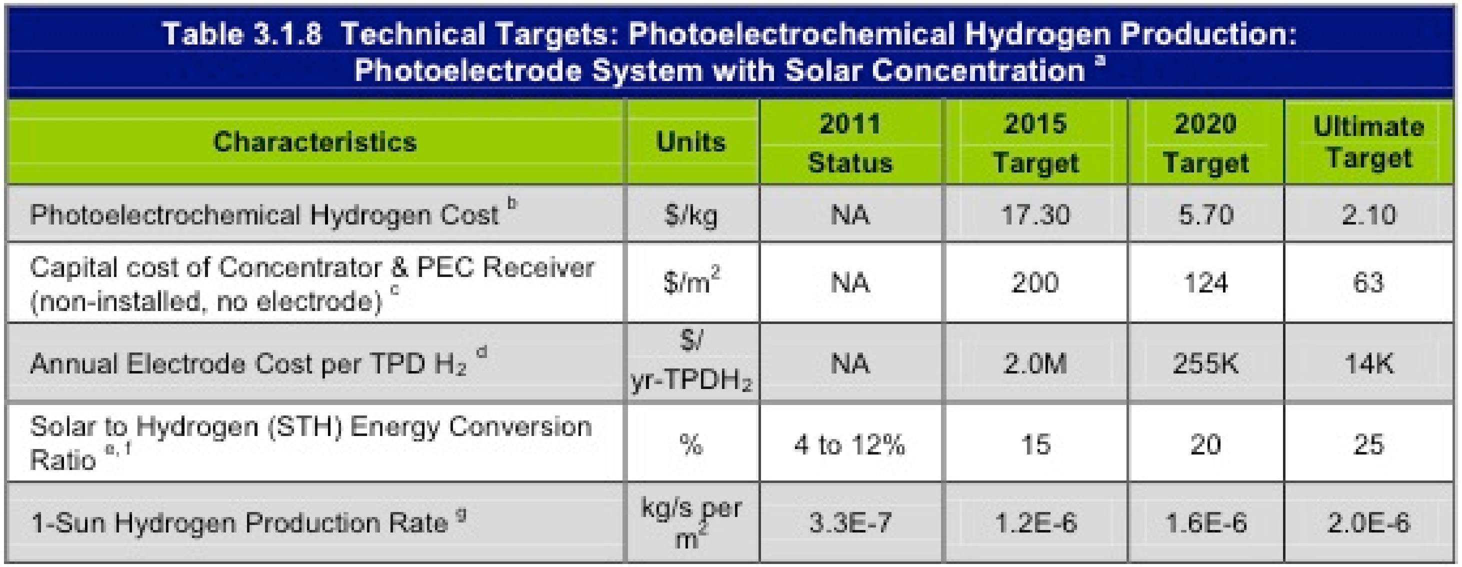


Table 3.1.8 Technical Targets: Photoelectrochemical Hydrogen Production: Photoelectrode System with Solar Concentration [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Photoelectrochemical Hydrogen Cost [b]	\$/kg	NA	17.30	5.70	2.10
Capital cost of Concentrator & PEC Receiver (non-installed, no electrode) [c]	$\$/m^2$	NA	200	124	63
Annual Electrode Cost per TPD H_2 [d]	\$/ yr-$TPDH_2$	NA	2.0M	255K	14K
Solar to Hydrogen (STH) Energy Conversion Ratio [e, f]	%	4 to 12%	15	20	25
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	3.3E-7	1.2E-6	1.6E-6	2.0E-6

Relevance

DOE EERE Multi-Year Research, Development, and Demonstration Plan

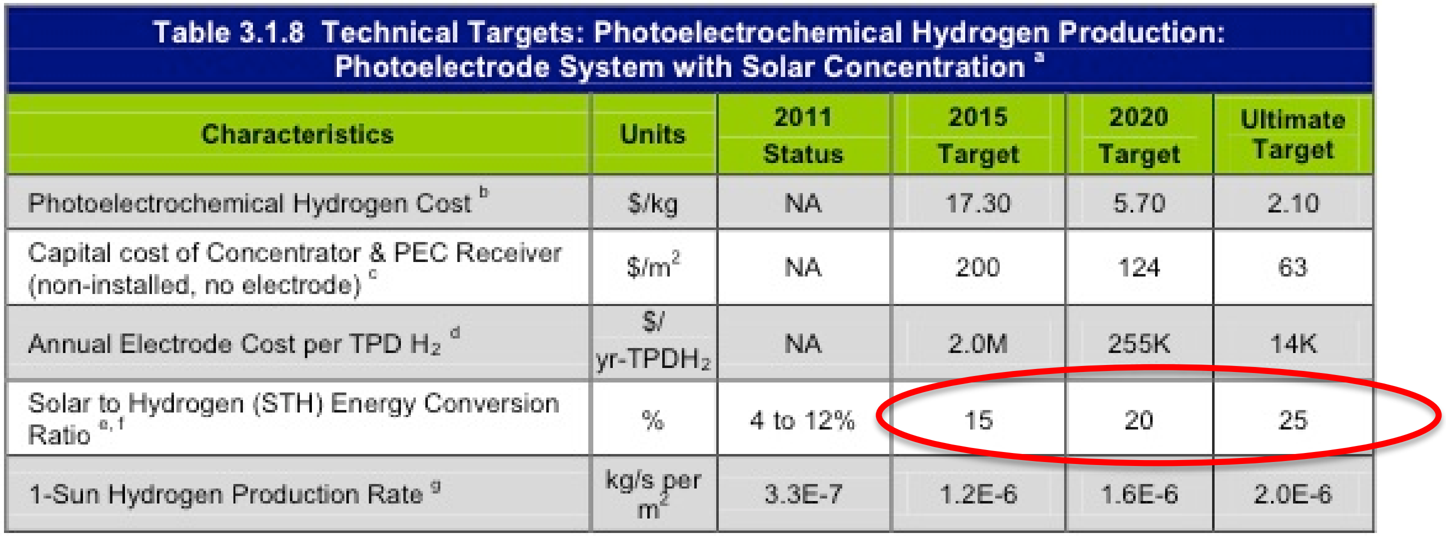
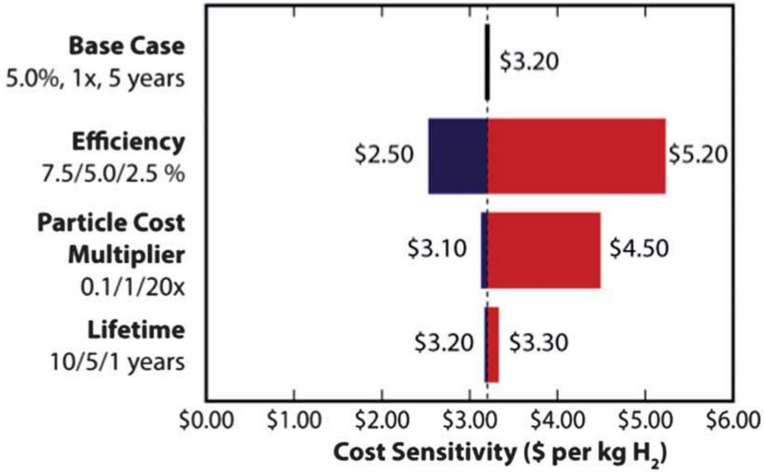


Table 3.1.8 Technical Targets: Photoelectrochemical Hydrogen Production: Photoelectrode System with Solar Concentration [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Photoelectrochemical Hydrogen Cost [b]	\$/kg	NA	17.30	5.70	2.10
Capital cost of Concentrator & PEC Receiver (non-installed, no electrode) [c]	\$/m^2	NA	200	124	63
Annual Electrode Cost per TPD H_2 [d]	\$/ yr-TPDH_2	NA	2.0M	255K	14K
Solar to Hydrogen (STH) Energy Conversion Ratio [e, f]	%	4 to 12%	15	20	25
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	3.3E-7	1.2E-6	1.6E-6	2.0E-6

Technoeconomic analysis for a type 4 (10x concentrator) PEC reactor



Pinaud et al. *Energy Environ. Sci*. **6**, 1983 (2013)

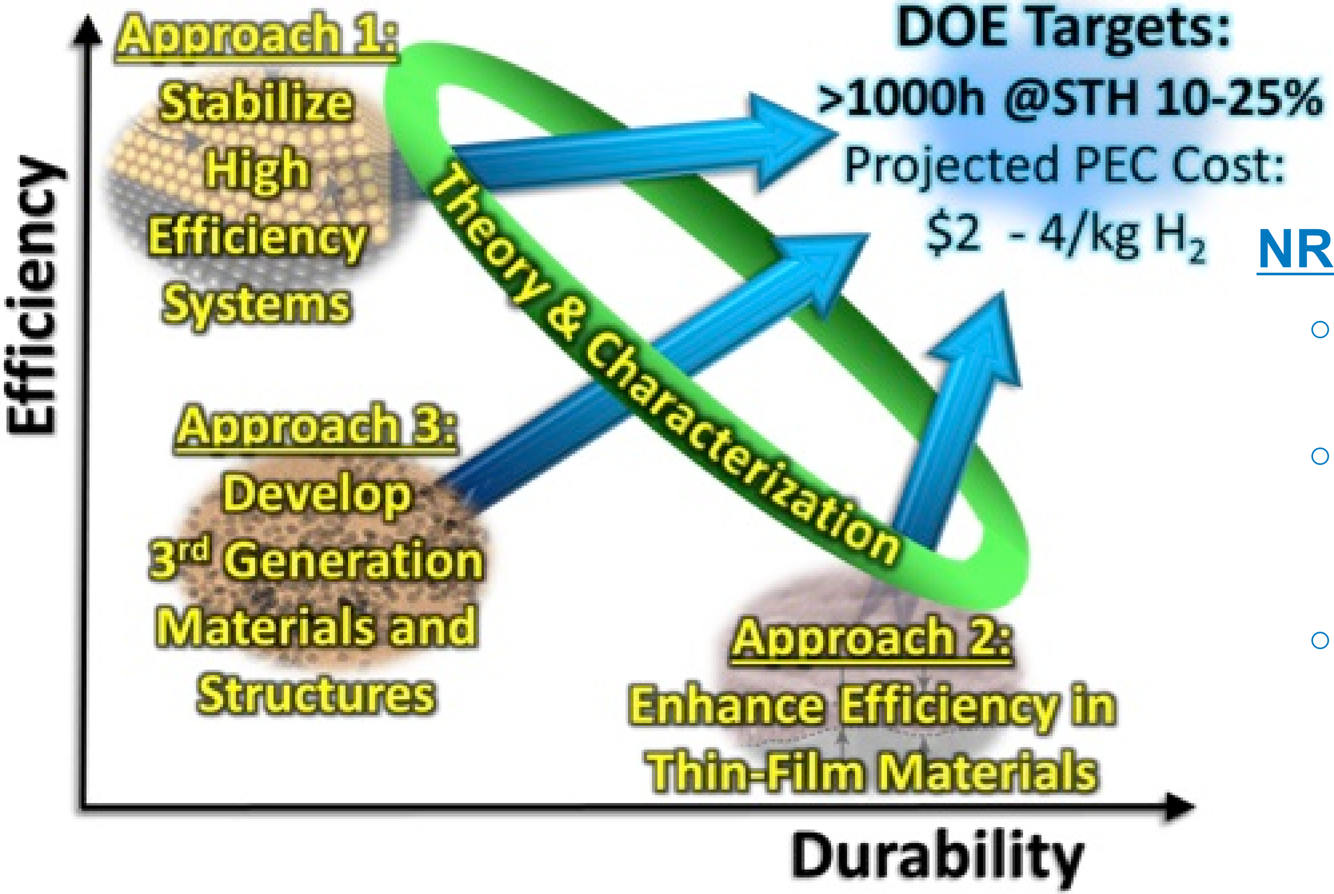
Project Guiding Principles

- Primary focus is on efficiency, the largest lever to reduce H_2 costs according to technoeconomic analysis
- Scalability is primary selection criterion, more important than earth abundance
- Absorber cost and durability (lifetime) issues can be addressed through engineering

Approach

EERE: Applied R&D to develop cost-effective large-scale systems
NSF: Use-inspired basic research (theory, synthesis, characterization)
Emphasis on collaboration across disciplines and institutions

The US DOE PEC Working Group approach towards efficient and durable solar H_2 production



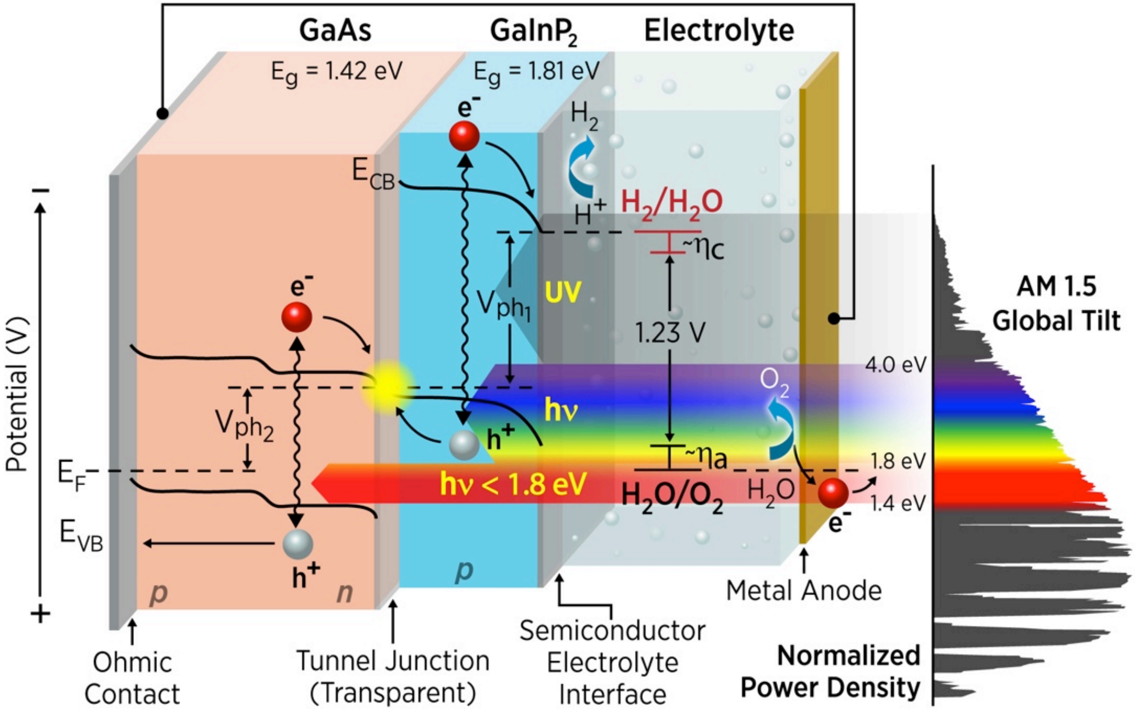
NREL-led Project Focus:

- Extend durability of highly efficient materials
- Ensure efficiencies are not compromised by durability treatments
- Investigate new materials that can achieve ultra-high future efficiency goals

Approach – Project Overview

Maximize efficiency first then focus on durability via surface modifications, investigate lower-cost synthesis once material has been identified

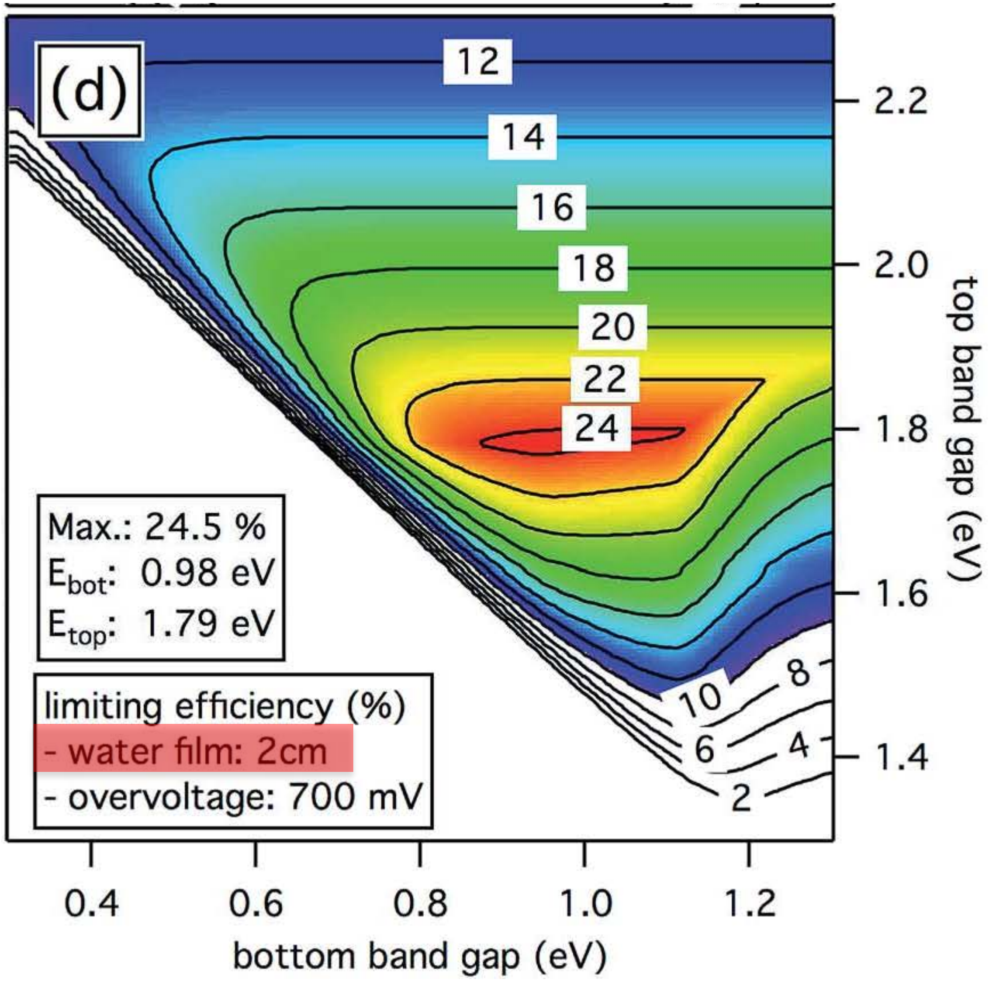
- **Tandem absorbers**
  - Task 1: Demonstrating attainable efficiencies
    - III-Vs by MOCVD (NREL)
  - Task 2: higher-risk, lower-cost approaches
    - $In_xGa_{1-x}N$ tandems (LANL)
    - III-V-N on Si tandems (NREL)
    - Coupled photoanode-photocathode systems (Hawaii, NREL)



- **Surface modifications – spectroscopy (UNLV) and modeling (LLNL)**
  - Ion-implantation & flash sputtering (NREL)
  - Thin coatings by atomic layer deposition (NREL, CU)
  - Molybdenum disulfide coatings (Stanford)
- **Benchmarking, prototyping, & demonstration**
  - Photoreactor design and outdoor device testing (NREL, JCAP-Solar Fuel Hub)

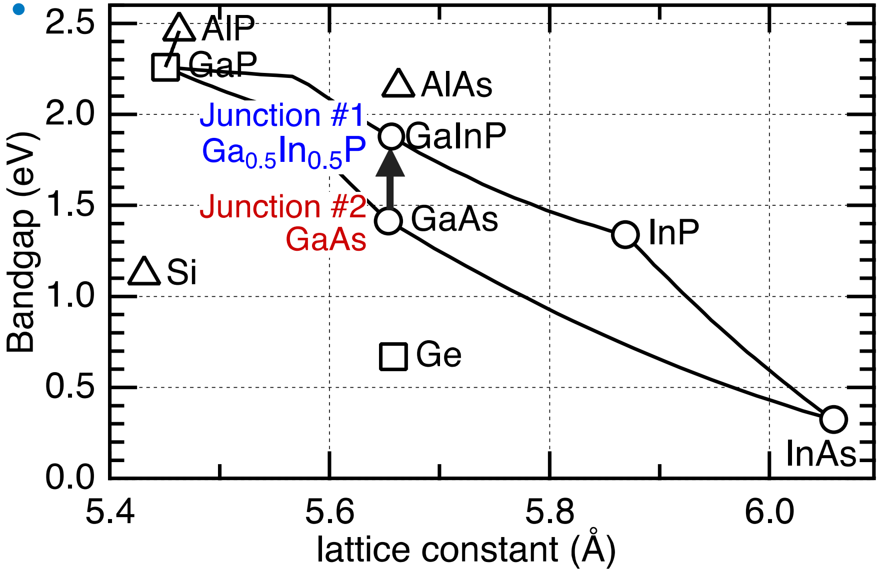
Approach: High Efficiency via Tandems

Döscher et al. *Energy Environ. Sci.*, **7** 2956 (2014)



- Exceeding 20% solar-to-hydrogen (STH) feasible
- Reactors with low water penetration for 25% STH
- $GaInP_2$/GaAs (1.8 eV, 1.4 eV) not optimal

- Traditional MOCVD requires lattice matching from substrate through all epi-layers to maintain high material quality
- Metamorphic growth removes “vertical-only” constraint by incorporating a transparent, step-graded layer to allow non-lattice matched absorbers
- Inverted Metamorphic Multijunction (IMM) growth: top junction grown first, device layers removed from substrate, could potentially be re-used

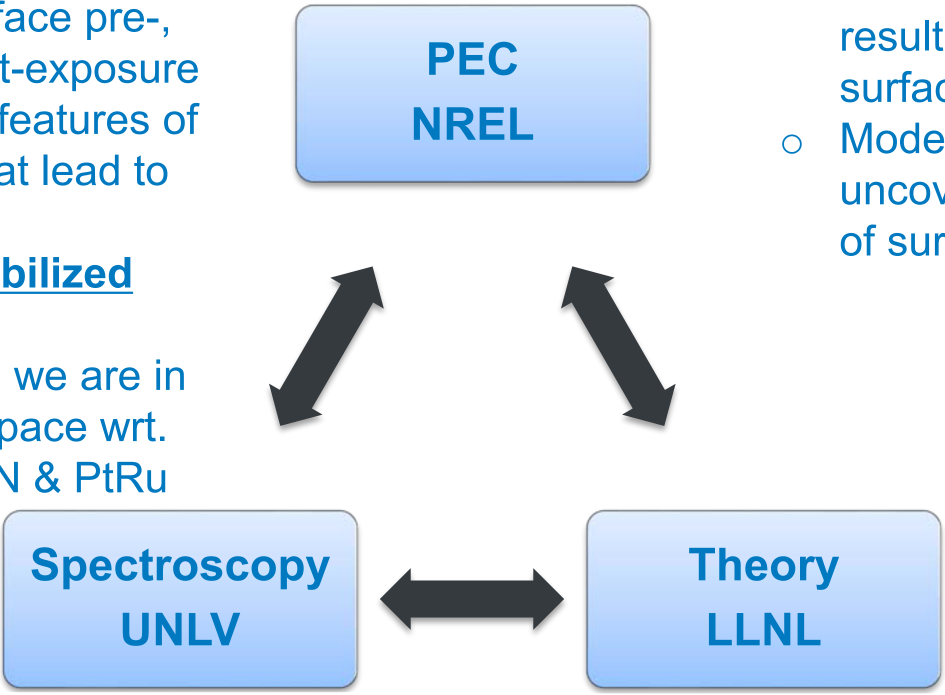


Approach: Surface Validation Team

Understanding and remedying semiconductor photocorrosion at PEC interfaces is a complex task that has benefitted significantly from a collaborative approach which teams experts with unique capabilities and resources

- **Heske group at UNLV**
  - XPS, XAS, XES, IPES, UPS, AFM
    - Some measurements at Advanced Light Source (ALS)
  - Snapshots of surface pre-, intermediate, post-exposure
  - Identify common features of and conditions that lead to corrosion
  - **Characterize stabilized surfaces**
    - Show where we are in parameter space wrt. amounts of N & PtRu

- **Ogitsu group at LLNL**
  - Develop theoretical tool chest for modeling PEC systems
  - Simulate x-ray spectra to correlate UNLV experimental results with surface/near surface compositions
  - Model III-V surfaces to uncover the key mechanisms of surface corrosion

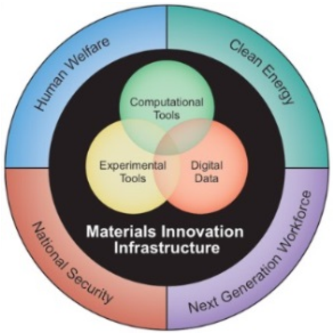


PEC
NREL

Spectroscopy
UNLV

Theory
LLNL

Advanced Materials Manufacturing (AMM) / Materials Genome initiative (MGI)



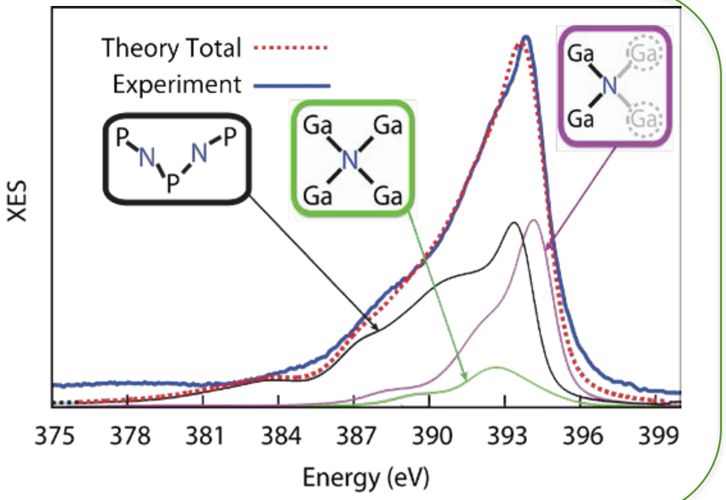
Innovative materials discovery and development for faster product development. Key elements include:

- Integrating experiment, computation, and theory
- Making digital data accessible
- Creating a world-class materials workforce
- Leading a culture shift in materials research

Surface Validation: Photocorrosion of III-V materials with Heske (UNLV), Ogitsu (LLNL)

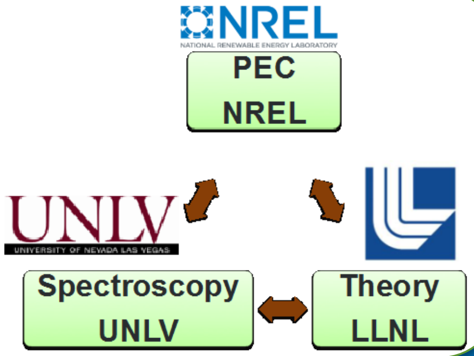
Correlate Spectroscopy with Theory on Nitrided p-GaInP$_2$ System: Establish Base for Predictive Capabilities

- Based on observation that nitridation led to stabilized GaInP$_2$ surface: Model the *local* nitrogen environment to understand measured spectra
- Theoretical N_2^+ implanted GaInP$_2$ nitrogen K-edge XES spectrum by LLNL constructed from various types of nitrogen impurity states as well as the experimental XES measured by UNLV group at LBNL synchrotron



MGI Elements Incorporated: theory, modeling, experimental

- ✓ Encourage and enable integrated R&D
- ✓ Enable creation of accurate, reliable simulations
- ✓ Support creation of accessible materials data repository (sharepoint)
- ✓ Provide opportunities for integrated research experiences



Approach: Pathways to III-V Semiconductor Cost Reductions

- **Optical concentration**
  - 10x-100x uses less absorber
- **Re-use substrate**

  NREL report PR-6A00-60126
  - Epitaxial lift-off

    Phys. Status Solidi **202,** 501–508 (2005)
  - Multilayer epitaxial assemblies

    Appl. Phys. Lett. **102,** (2013)
  - Spalling

    Appl. Phys. Lett. **100,** 053901 (2012)
  - Laser lift-off

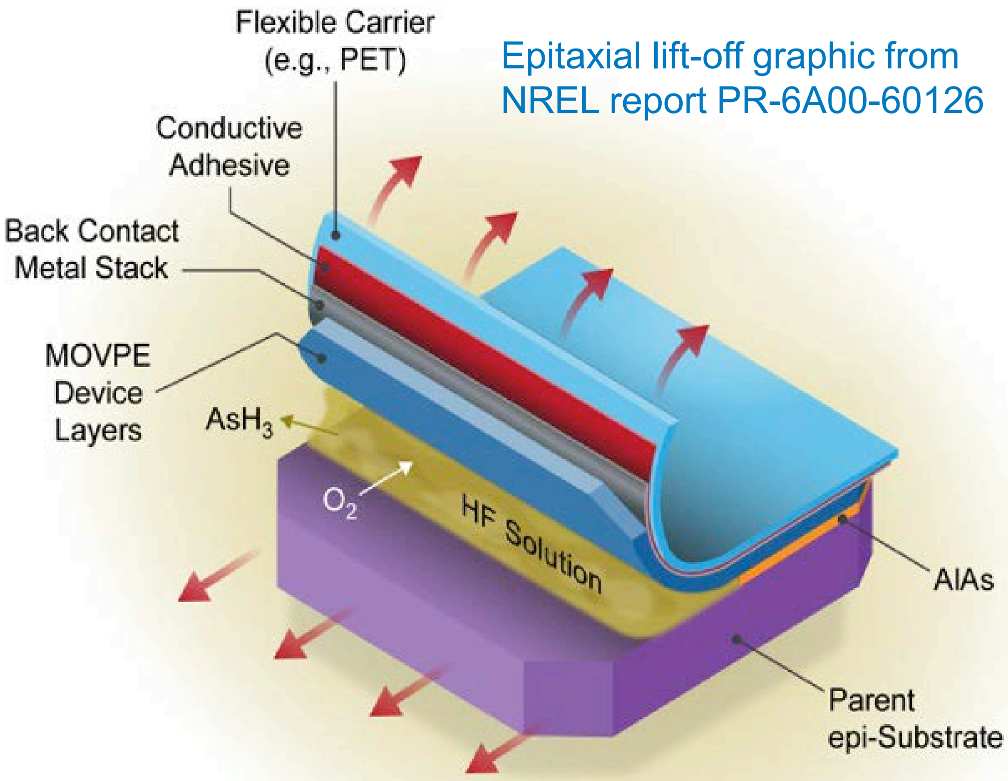
    MRS Comm. 1–5 (2015). doi:10.1557/mrc.2015.2
- **Alternative substrate**

  NREL report PR-6A00-60126
  - III-V on Si

    Semicond. Sci. Technol. **17,** 769–777 (2002)
  - Metal foil
    - Close-space vapor transport

      J. Appl. Phys. **112,** 123102 (2012)
    - Ion beam assisted deposition

      Appl. Phys. Lett. **105,** 092104 (2014)



Epitaxial lift-off graphic from NREL report PR-6A00-60126

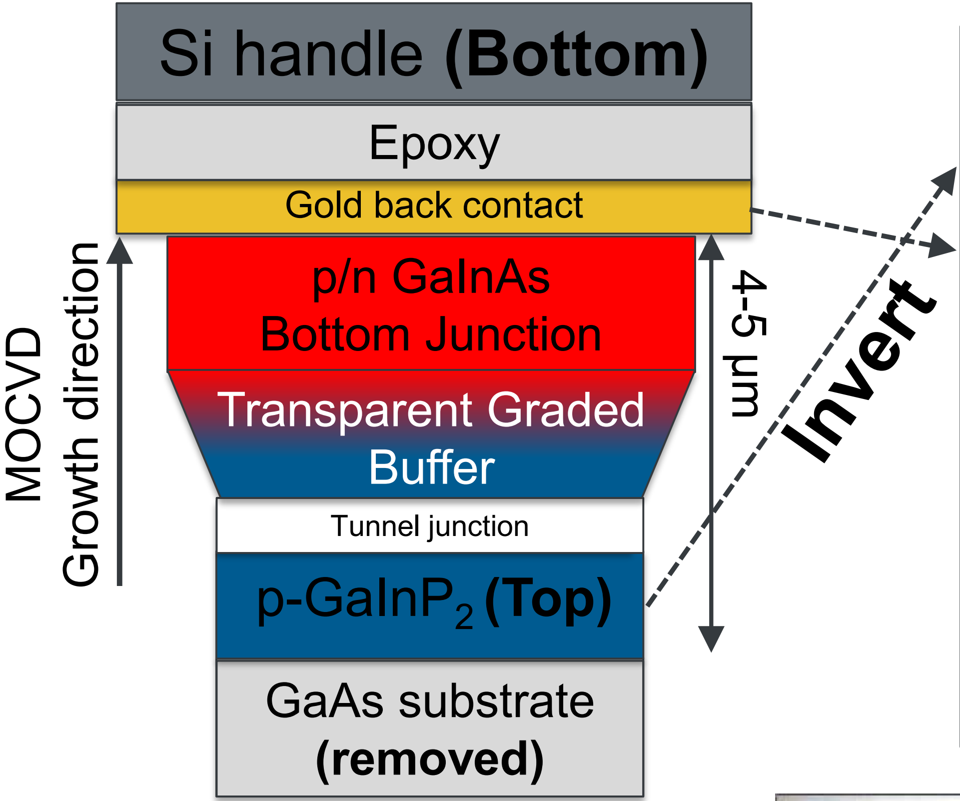
- **Alternative precursors**
  - Close-spaced vapor transport

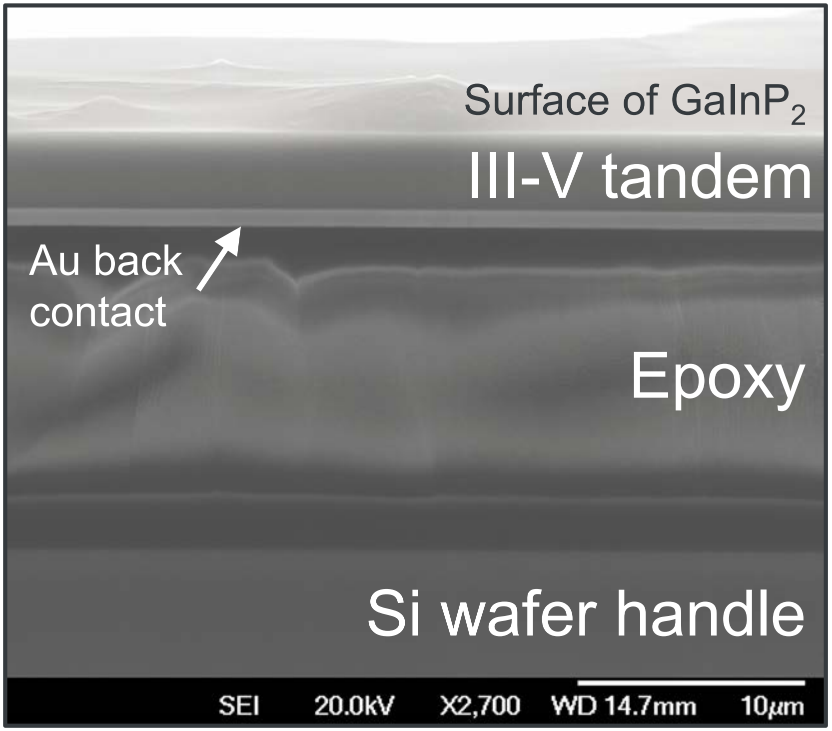
    ACS Appl. Mater. Interfaces **4,** 69–73 (2012)
  - Hydride vapor phase epitaxy

    J. Appl. Phys. **113,** 174903 (2013)

This is a very active area of research that includes commercial cell manufacturers and funding support from ARPA-E.

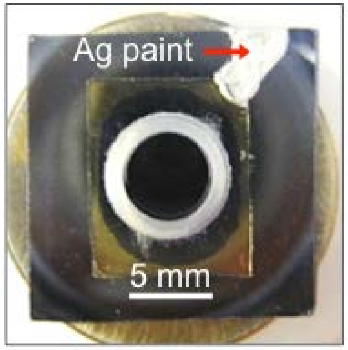
Progress: Demonstration of IMM for PEC



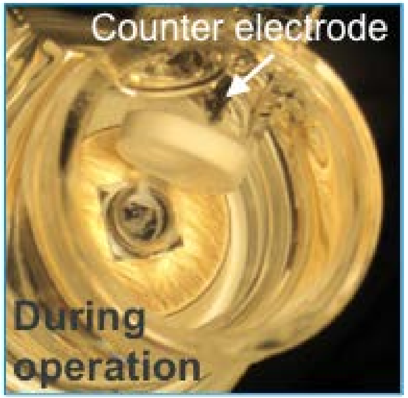


Inverted growth – light-facing wider bandgap grown first

- Top junction lattice-matched to substrate
- Device transferred to handle material and substrate removed
  - Potential substrate re-use
  - Reflective back contact

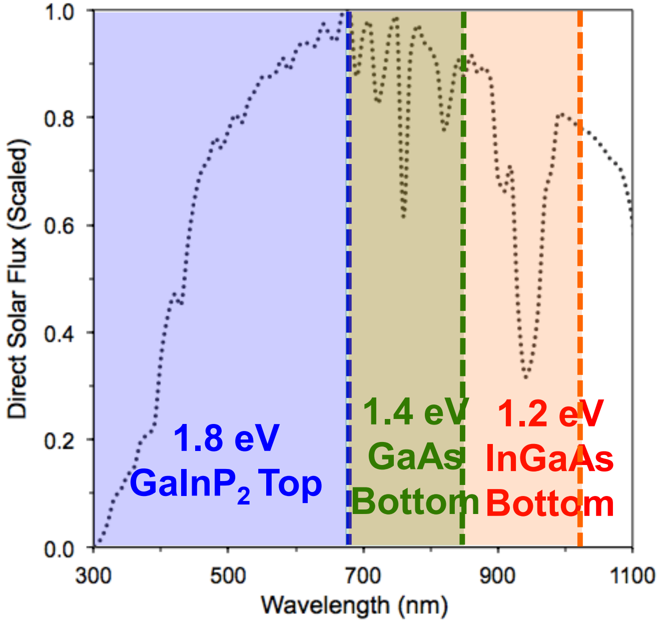


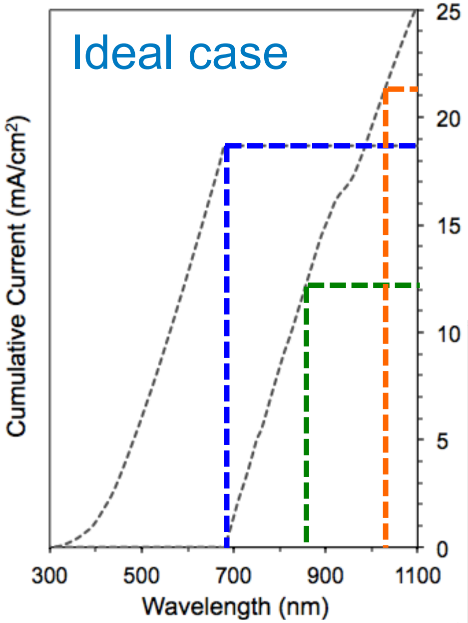
Compression cell



James Young

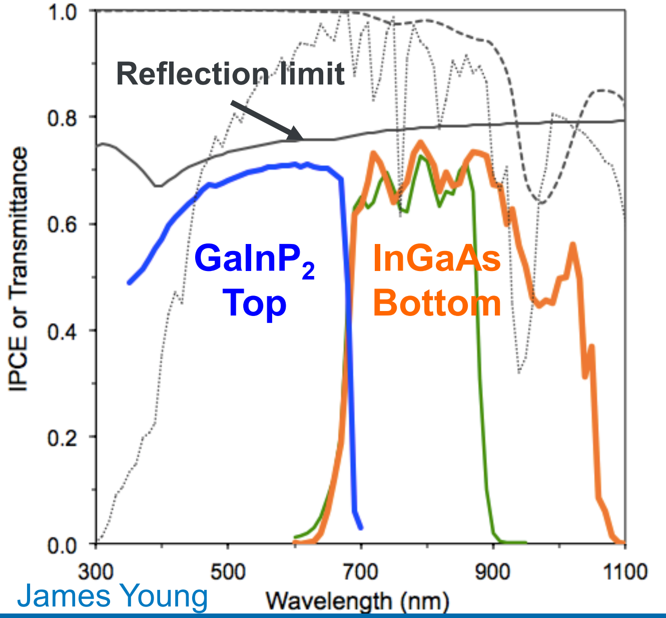
Progress: IMM Devices for Increased Utilization of Solar Spectrum – On the Path to Higher Efficiency

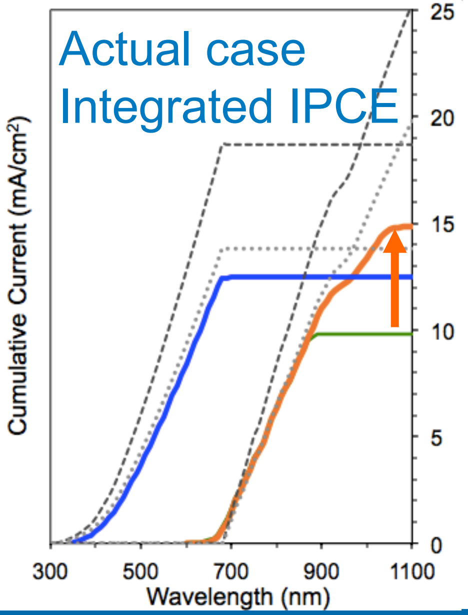


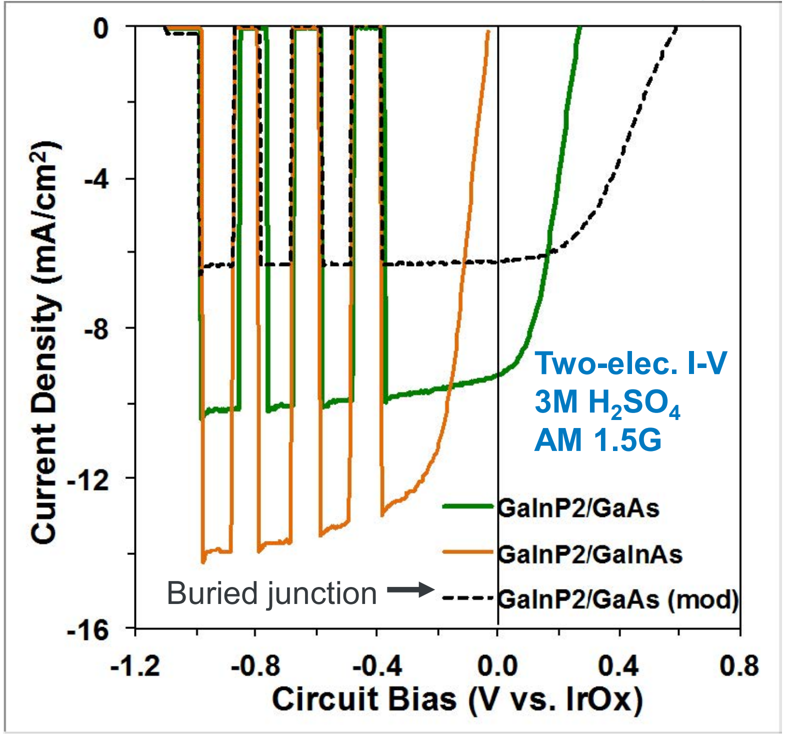


Increasing bandgap-limited current

- Absorber junctions in series: voltages add, current limited by lower value (current matching)
- Lowered bottom junction increases total photon flux but lowers voltage







Increased device current

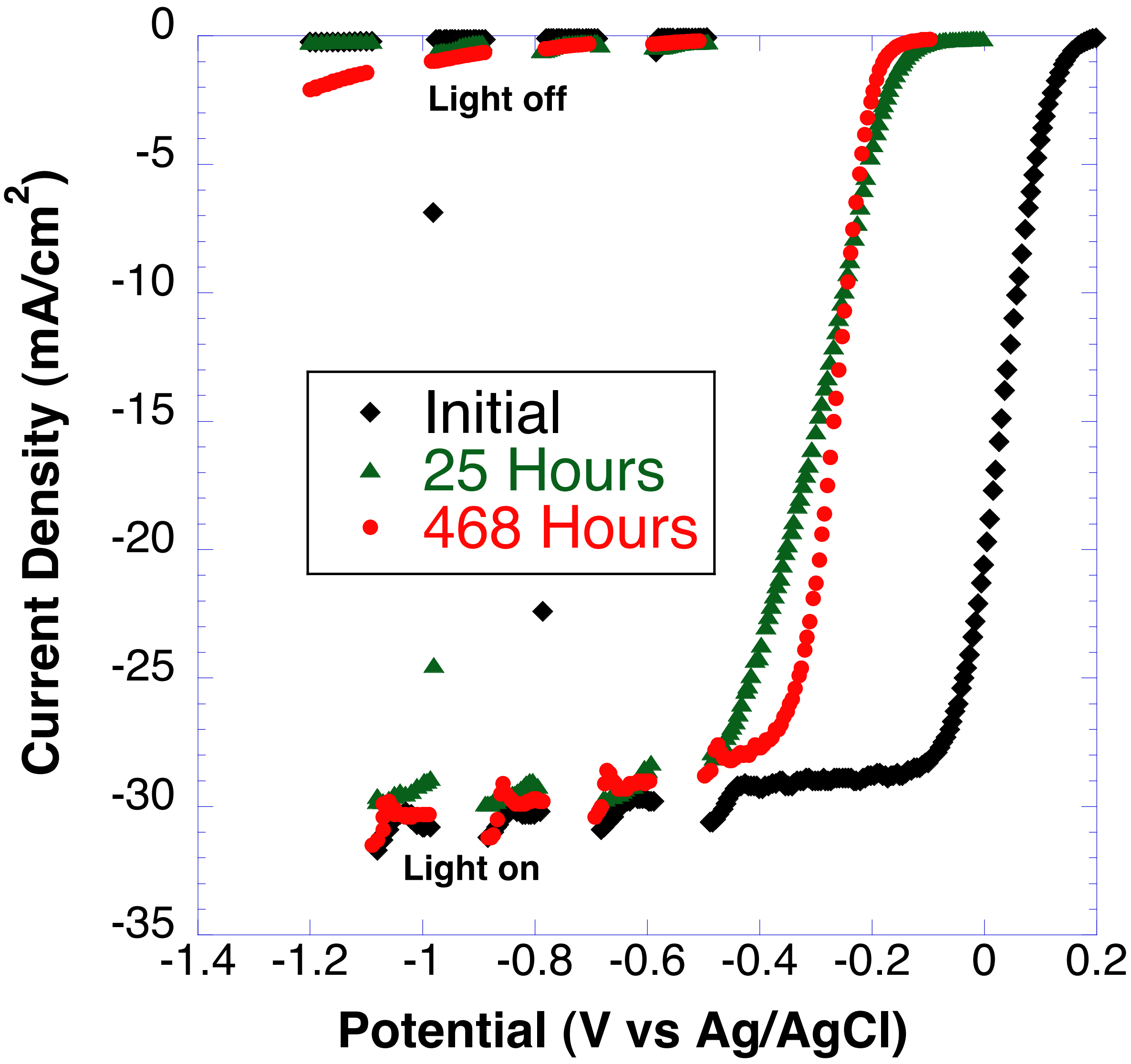
Buried junction to improve voltage

Anti-reflection to smash world-record

James Young

Progress: Met 400-hour Milestone – 468 Hours of Durability with N_2^+/PtRu

Fouling of the electrode was minimized by changing the electrolyte every weekday

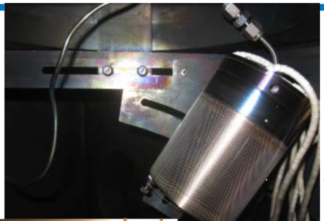


- p-GaAs with N_2^+ ion bombardment and PtRu sputtering
- Operated at 15mA/cm^2 in 3M H_2SO_4 with 1mM Triton X-100
- Some fouling still occurred
- Cleaning in methanol and nitric acid restored light-limited photocurrent to original value
- Photocurrent onset potential was degraded
  - Catalyst deactivation?
  - Catalysts loss?

Over 150 hrs durability with MoS_2
Jaramillo (Stanford) poster PD119

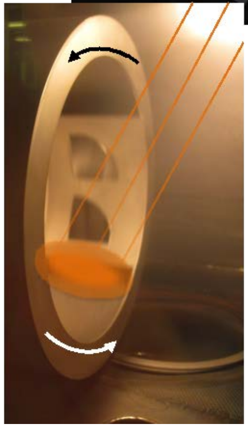
Progress: Mapping Pt & Ru Distribution from N_2^+/PtRu Surface Modification

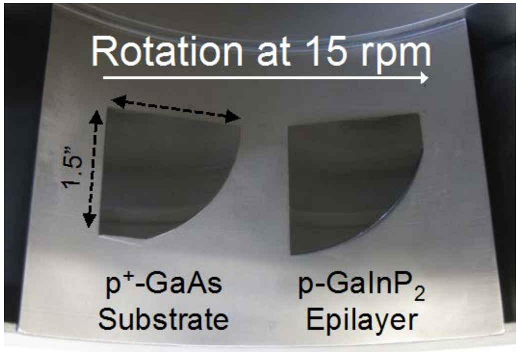
- Simultaneously treated GaAs substrate and $GaInP_2$ epilayers
- Digested entire GaAs wafer, portions of $GaInP_2$ in aqua regia and Pt, Ru determined by ICP-MS
- Reported in thickness (nm) of compact film
- Results:
  - Nitridation step significant source of PtRu
  - Fairly uniform spatial distribution
  - Full treatment on GaAs much greater than sum of parts



N_2^+ implantation: 0.7 mTorr N_2, 12 mA beam, 9 minutes @ 15 rpm

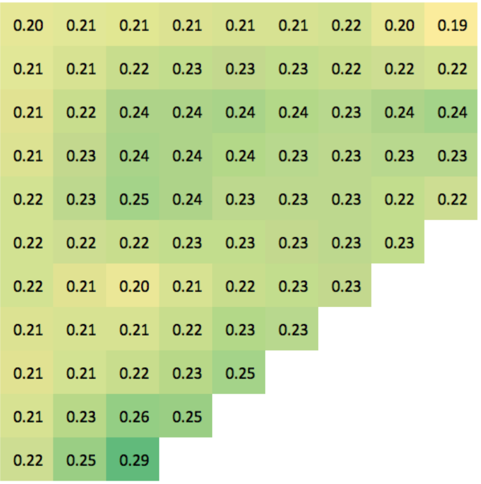
PtRu sputtering: 10 mTorr Ar, 20 W DC, 2 rotations @ 15 rpm





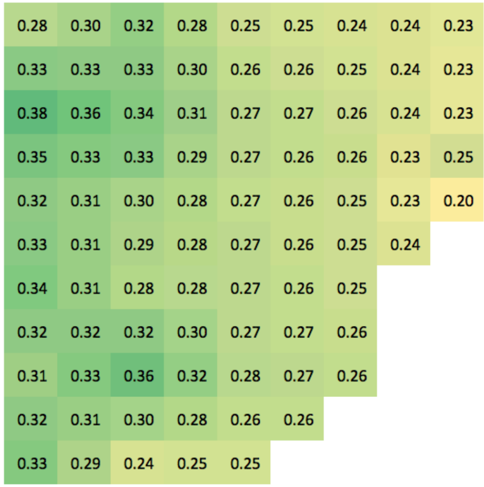
Treatment	p^+-GaAs Subs. Ru (nm)	p-$GaInP_2$ Epi. Ru (nm)	p^+-GaAs Subs. Pt (nm)	p-$GaInP_2$ Epi. Pt (nm)
Nitridation	0.22 ±0.02	0.25 ±0.07	0.18 ±0.02	0.19 ±0.06
Sputtering	0.28 ±0.04	0.17 ±0.01	0.19 ±0.02	0.13 ±0.01
Full	1.59 ±0.21	0.44 ±0.07	1.65 ±0.2	0.33 ±0.05

Nitridation



0.20	0.21	0.21	0.21	0.21	0.21	0.22	0.20	0.19
0.21	0.21	0.22	0.23	0.23	0.23	0.22	0.22	0.22
0.21	0.22	0.24	0.24	0.24	0.24	0.23	0.24	0.24
0.21	0.23	0.24	0.24	0.24	0.23	0.23	0.23	0.23
0.22	0.23	0.25	0.24	0.23	0.23	0.23	0.22	0.22
0.22	0.22	0.22	0.23	0.23	0.23	0.23	0.23	
0.22	0.21	0.20	0.21	0.22	0.23	0.23		
0.21	0.21	0.21	0.22	0.23	0.23			
0.21	0.21	0.22	0.23	0.25				
0.21	0.23	0.26	0.25					
0.22	0.25	0.29						

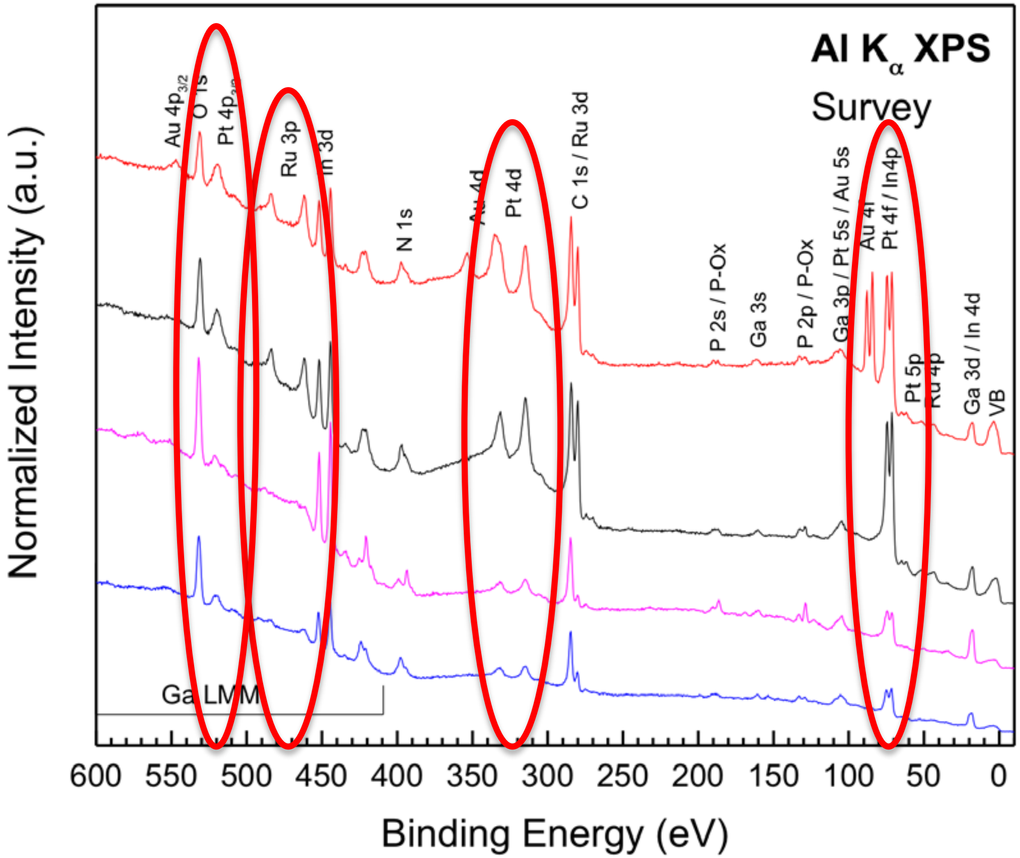
PtRu Sputtering



0.28	0.30	0.32	0.28	0.25	0.25	0.24	0.24	0.23
0.33	0.33	0.33	0.30	0.26	0.26	0.25	0.24	0.23
0.38	0.36	0.34	0.31	0.27	0.27	0.26	0.24	0.23
0.35	0.33	0.33	0.29	0.27	0.26	0.26	0.23	0.25
0.32	0.31	0.30	0.28	0.27	0.26	0.25	0.23	0.20
0.33	0.31	0.29	0.28	0.27	0.26	0.25	0.24	
0.34	0.31	0.28	0.28	0.27	0.26	0.25		
0.32	0.32	0.32	0.30	0.27	0.27	0.26		
0.31	0.33	0.36	0.32	0.28	0.27	0.26		
0.32	0.31	0.30	0.28	0.26	0.26			
0.33	0.29	0.24	0.25	0.25				

Ru loading on GaAs (nm)

Progress: Work with Surface Validation Partner (UNLV) to Understand PtRu Loading Now vs. Then



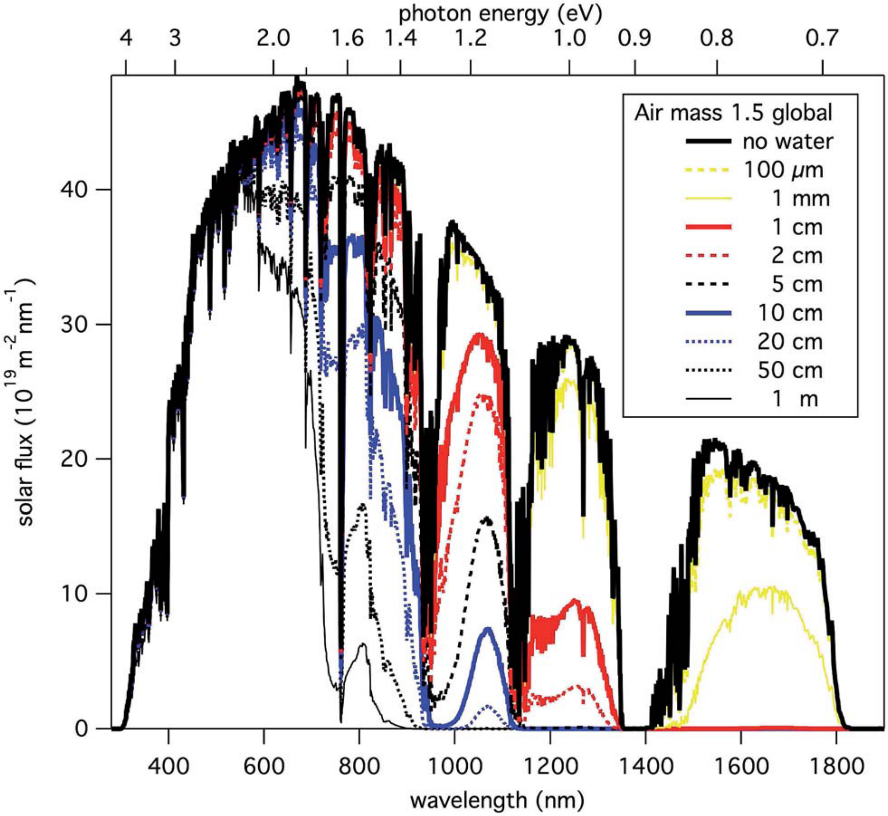
Not where we want to be in terms of N and PtRu loading for max durability

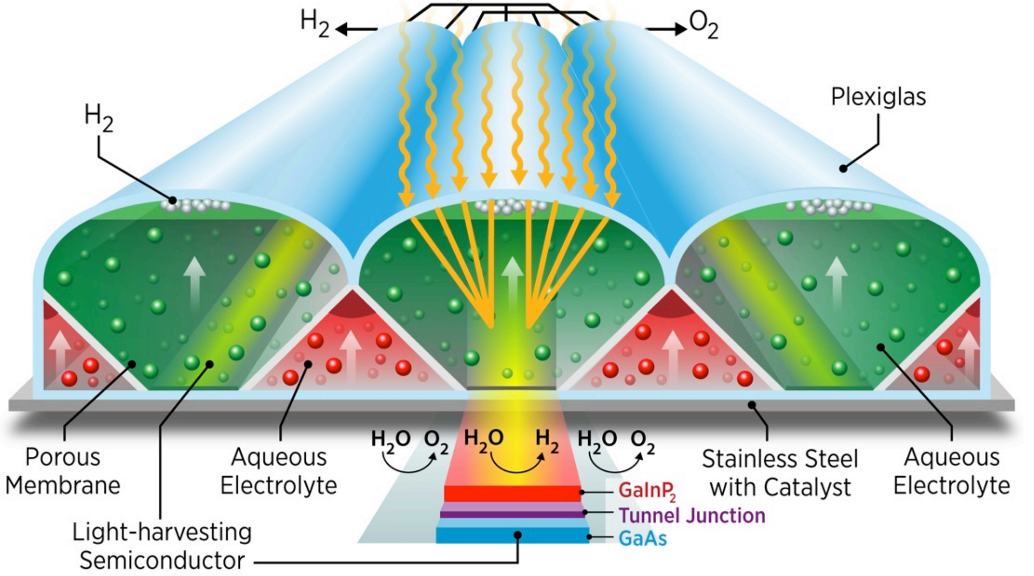
	Approximate % of treated $GaInP_2$ samples with desired durability
New “standard” treatment: (New ion gun, PtRu sputtering)	30%
New “standard” treatment: (New ion gun, PtRu sputtering)	30%
First repetition of protection: (Old ion gun, PtRu sputtering)	90%
Original “magic” sample: (Old ion gun, no sputtering)	90%

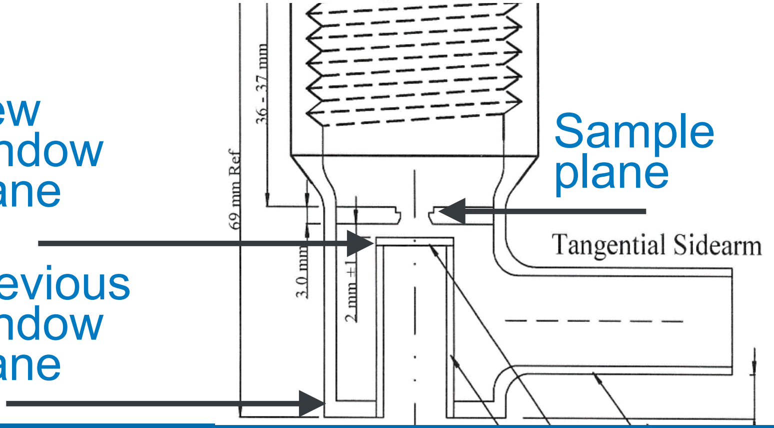
- X-ray photoelectron spectroscopy (XPS) by Monika Blum at UNLV reveals significantly (order of magnitude) greater noble metal loading on newer samples
- “Magic” samples had more N (by XES) and less PtRu than current parameter space
- Can’t achieve low PtRu and high N with current set-up
- Future: new non-air-exposed samples to UNLV to evaluate N loading & distribution

Progress: Reactor Design

- Initial design had optical concentration from curved front window and large pathlength through electrolyte
- Electrolyte absorbs large fraction of useable infrared photons
- New design for lab characterization and demonstration that reduces electrolyte pathlength from 2 cm to 4 mm







New window plane

Sample plane

Previous window plane

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **"It is unclear what impact lifetime has on cost projections. A tornado plot would help"**
  - Response: We have included a tornado plot for a type 4 (concentrator) PEC reactor that shows the impact of lifetime on hydrogen cost projections on slide 4.
- **"The singular weakness of this project is the disconnect with the fabrication team for III-V material. It appears the material is produced with a foundry-type relationship. It would be better served if the material fabrication was a more integral part of the project, with shared ownership in the success."**
  - Response: We have significantly strengthened our interaction with the III-V group in several ways. We wrote in dedicated, direct funding for synthesis in the FOA proposal, we share a postdoc (Henning Döscher) that has expertise in PEC and III-V synthesis that designs and submits run recipes with our input, and we have regular meetings with the III-V group. The enhanced confederation has already borne fruit: the co-inventors on our provisional patent application on IMM III-Vs for photoelectrolysis is a combination of PEC and III-V group members.

Collaborations

- Partners (extensive collaboration with all)
  - University of Nevada Las Vegas
    - Partner in surface validation project
  - Lawrence Livermore National Laboratory
    - Partner in surface validation project
  - University of Hawaii (PD116)
    - Gaillard group – Partner on dual photoelectrode approach; sample exchange and validation
  - Los Alamos National Laboratory
    - Mark Hoffbauer – InGaN samples
  - Stanford University (PD119)
    - Jaramillo group – Key partner in MoS_2 for stabilization efforts
  - Technische Universität Ilmenau, (Germany)
    - Henning Döscher, Marie Curie fellow, is a member of our PEC group and NREL's III-V group
  - Technical University of Denmark
    - Ib Chorkendorf – DTU hosts one of our students, sample exchange
  - Colorado School of Mines
    - Graduate, postdoc and assistant professor research associates; electron microscopy and XPS user facilities; sample exchange
  - University of Colorado-Boulder
    - Two NSF-graduate research fellow associates under Steve George and Art Nozik are part of our group
  - University of Louisville
    - Sunkara group – novel III-Vs ($GaAs_xSb_{1-x}$)
    - Joint characterizations/publication
  - University of Oregon
    - Boettcher group – Student exchange, joint III-V-N PEC characterizations
  - Helmholtz-Zentrum, Berlin (Germany)
    - Roel Van de Krol – We host student studying transparent OER catalysts

Remaining Challenges and Barriers

- **Efficiency:**
  - Push solar-to-hydrogen efficiency from 12% to beyond 20% for meeting ultimate DOE targets
- **Durability:**
  - Extend our 0.2 year durability to 2 years in the short-term and 10 years long-term
  - More realistic real-world durability assessments
  - Identification and control of non-obvious but stability-relevant process parameters
- **Semiconductor costs:**
  - Reduce synthesis costs by factor of 10 compared to current cost of small-batch III-V materials
- **System testing:**
  - Identify promising photoreactor designs and components
    - Window/body material, sealant/epoxy, membrane, counter electrode

Future Work– Towards *Economical* Hydrogen

In order to achieve the EERE plant-gate, untaxed cost targets of \$1-2/kg H_2 (1kg H_2 = 1gge) requires a PEC system that has 25% solar-to-hydrogen (STH) efficiency, a semiconductor cost around \$150/m^2, and 10 years of stability.

- **Efficiency**
  - Demonstrate >15% STH efficiency at short circuit for at least 1 hour (milestone)
  - Push efficiency by testing lower bandgap configurations that sacrifice voltage to achieve higher currents (efficiencies)
- **Durability**
  - Demonstrate 875 hours of durability at current density equivalent to 15% STH under 1 sun using three surface passivation approaches; work with surface validation team to understand mechanism of protection
- **Semiconductor Cost**
  - Simulate photoreactor performance with higher concentration using multi-physics modeling to evaluate what levels are practically achievable
  - Request samples for PEC characterization from others developing innovative III-V synthesis routes being developed by other DOE programs (SunShot, arpa-e)
    - Epitaxial lift-off, spalling, HVPE, CSVT
- **Photoreactor Prototyping**
  - Design and build photoreactors with low optical concentration and low electrolyte penetration depth for on-sun measurements on a solar tracker.

Project Summary

Relevance:	Spearheading research in high-efficiency materials in order to meet DOE metrics and objectives for solar-hydrogen generation
Approach:	Focus on high-efficiency III-V crystalline semiconductor systems, an NREL core competency: investigation of new materials and configurations as well as stabilization of $GaInP_2$ surface
Technical Accomplishments:	Developed IMM III-V devices capable of accessing highest possible STH efficiencies, continued optimization of surface treatment conditions and PtRu quantification; GaAs durability – 468 hours of stability @ 15 mA/cm^2 (improvement on previous 315 hours @ 15 mA/cm^2); began collaborative effort with Stanford on MoS_2 protection of III-Vs; modeled absorption of sunlight by water and influence on attainable STH efficiencies – published manuscript and designed new cells based on results; along with UNLV made progress in understanding history of PtRu on $GaInP_2$
Collaborations:	Several ongoing, active collaborations with synthesis, modeling, and characterization groups
Proposed Future Work:	Push STH efficiency limits with IMM III-Vs; evaluate III-V-N/Si tandems for lower cost, higher stability alternative; examine stacked mechanical (dual electrode) tandems with Hawaii; push three surface passivation approaches (N_2^+/PtRu, MoS_2, ALD TiO_2) to achieve over 875 h durability; design and fabricate concentrator cells and commence regular outdoor testing

Technology Transfer Activities

- **Non-provisional patent filed on nitridation/sputtering surface protection (May 2014)**

Stable photoelectrode surfaces and methods

Publication number: US 20140332374 A1

ABSTRACT

Disclosed herein are methods of treating a semiconductor surface by nitridation and deposition of a ruthenium alloy. Also disclosed are semiconductors treated with these methods, their incorporation into photoelectrochemical cells, and their use in photoelectrochemical water splitting.

- **Provisional patent filed on using inverted metamorphic multi-junction III-Vs to achieve maximum attainable STH efficiency**

Acknowledgements

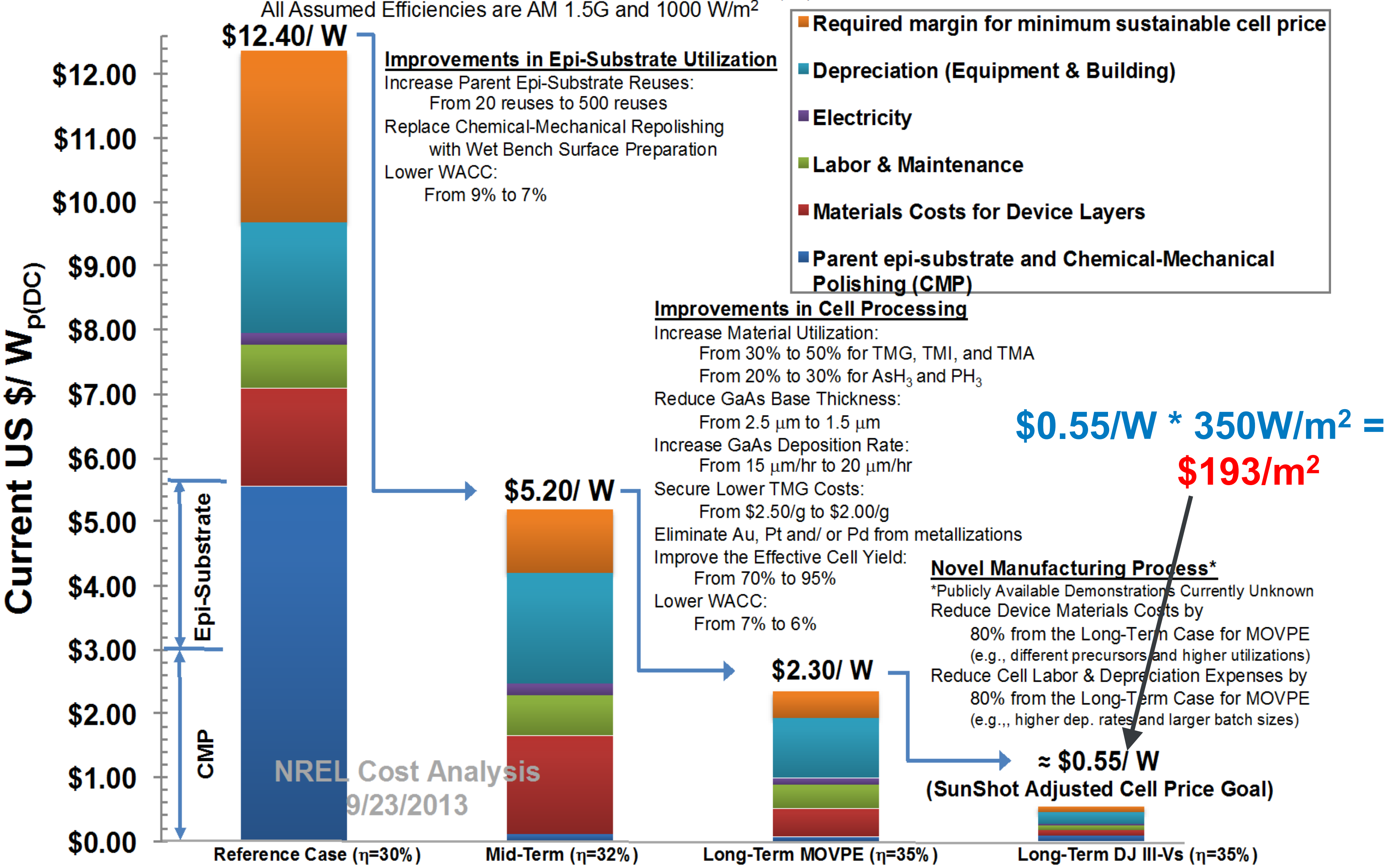
- John Turner – NREL
- Henning Döscher – NREL
- Heli Wang – NREL
- James Young – NREL/CU-Boulder (GS)
- Skye Rios – NREL/CU-Boulder (GS)
- Clay Macomber – NREL
- Huyen Dinh – NREL
- Anna Duda– NREL
- Arrelaine Dameron – NREL
- Andrew Norman – NREL
- All of our amazing collaborators noted throughout this presentation

Technical Back-Up Slides

Cost Model Results for MOVPE of Dual-Junction III-V Solar Cells by ELO

\$150 for 133 cm^2 Substrates, 400 nm of InGaP on top of GaAs, 500 $MW_{P(DC)}$ U.S. Manufacturing

All Assumed Efficiencies are AM 1.5G and 1000 W/m^2



Improvements in Epi-Substrate Utilization

Increase Parent Epi-Substrate Reuses:
From 20 reuses to 500 reuses
Replace Chemical-Mechanical Repolishing
with Wet Bench Surface Preparation
Lower WACC:
From 9% to 7%

Improvements in Cell Processing

Increase Material Utilization:
From 30% to 50% for TMG, TMI, and TMA
From 20% to 30% for AsH_3 and PH_3
Reduce GaAs Base Thickness:
From 2.5 μm to 1.5 μm
Increase GaAs Deposition Rate:
From 15 μm/hr to 20 μm/hr
Secure Lower TMG Costs:
From \$2.50/g to \$2.00/g
Eliminate Au, Pt and/ or Pd from metallizations
Improve the Effective Cell Yield:
From 70% to 95%
Lower WACC:
From 7% to 6%

Novel Manufacturing Process*

*Publicly Available Demonstrations Currently Unknown
Reduce Device Materials Costs by
80% from the Long-Term Case for MOVPE
(e.g., different precursors and higher utilizations)
Reduce Cell Labor & Depreciation Expenses by
80% from the Long-Term Case for MOVPE
(e.g.,, higher dep. rates and larger batch sizes)

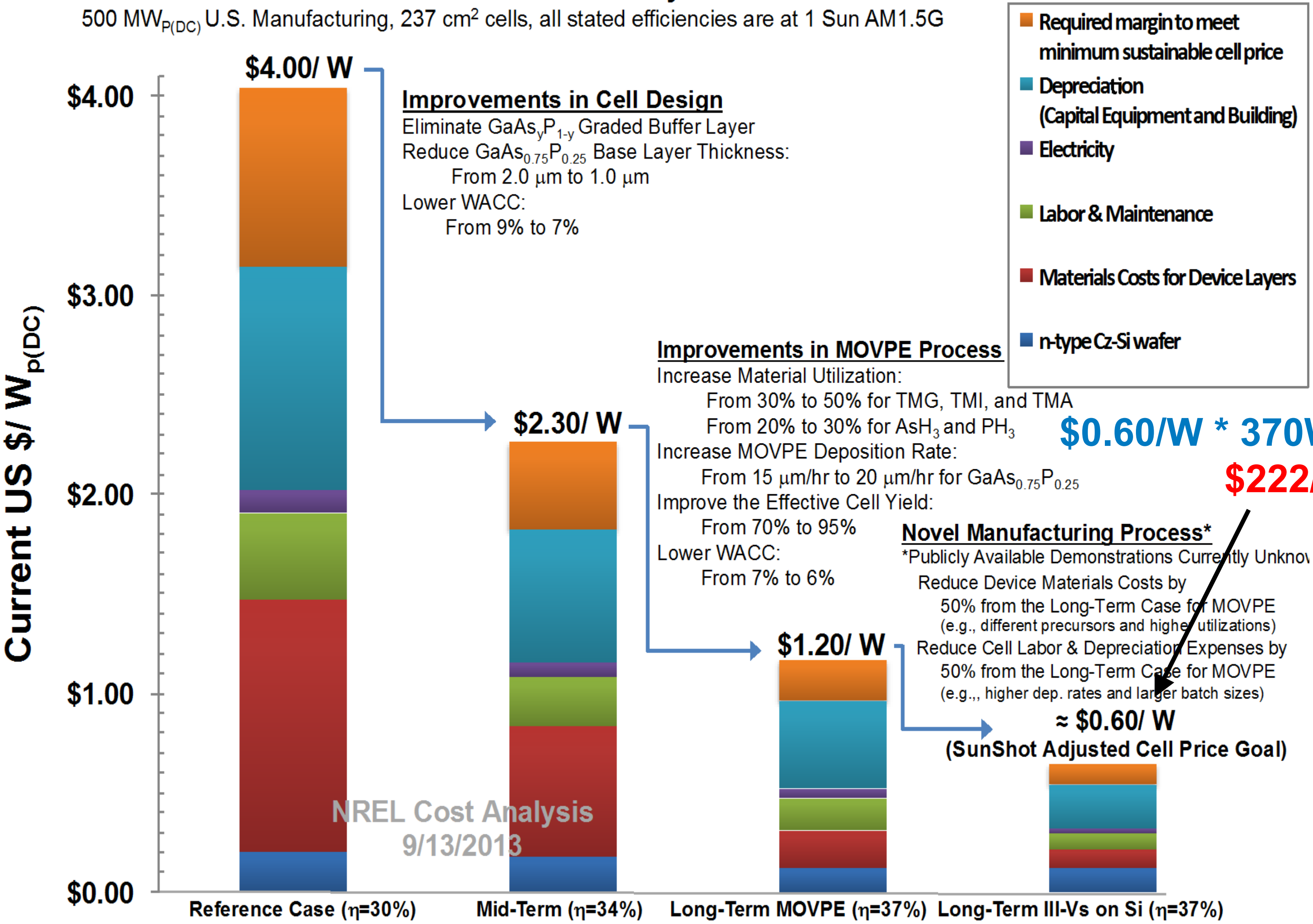
≈ \$0.55/ W
(SunShot Adjusted Cell Price Goal)

\$0.55/W * 350W/m² =
\$193/m²

Cost modeling projections for high-volume production of dual junction $GaInP_2$/GaAs PV on GaAs substrates using epitaxial lift-off (ELO) technology for substrate re-use. To get PEC material estimates in \$/m², \$/W is multiplied by 350W/m² (the efficiency). Modeling performed by Mike Woodhouse of NREL's Strategic Analysis group, with funding provided by the DOE SunShot Initiative, "A Manufacturing Cost Analysis Relevant to Single- and Dual-Junction Photovoltaic Cells Fabricated with III-Vs and III-Vs grown on Czochralski Silicon". **Publication Number NREL/PR-6A20-60126**

Cost Model Results for Dual-Junction Solar Cells by MOVPE of III-Vs on *Cz*-Si

500 $MW_{P(DC)}$ U.S. Manufacturing, 237 cm^2 cells, all stated efficiencies are at 1 Sun AM1.5G



Improvements in Cell Design
Eliminate $GaAs_yP_{1-y}$ Graded Buffer Layer
Reduce $GaAs_{0.75}P_{0.25}$ Base Layer Thickness:
From 2.0 µm to 1.0 µm
Lower WACC:
From 9% to 7%

Improvements in MOVPE Process
Increase Material Utilization:
From 30% to 50% for TMG, TMI, and TMA
From 20% to 30% for AsH_3 and PH_3
Increase MOVPE Deposition Rate:
From 15 µm/hr to 20 µm/hr for $GaAs_{0.75}P_{0.25}$
Improve the Effective Cell Yield:
From 70% to 95%
Lower WACC:
From 7% to 6%

Novel Manufacturing Process*
*Publicly Available Demonstrations Currently Unknow
Reduce Device Materials Costs by
50% from the Long-Term Case for MOVPE
(e.g., different precursors and higher utilizations)
Reduce Cell Labor & Depreciation Expenses by
50% from the Long-Term Case for MOVPE
(e.g.,, higher dep. rates and larger batch sizes)

≈ $0.60/ W
(SunShot Adjusted Cell Price Goal)

NREL Cost Analysis
9/13/2013

$0.60/W * 370W/m² =
$222/m²

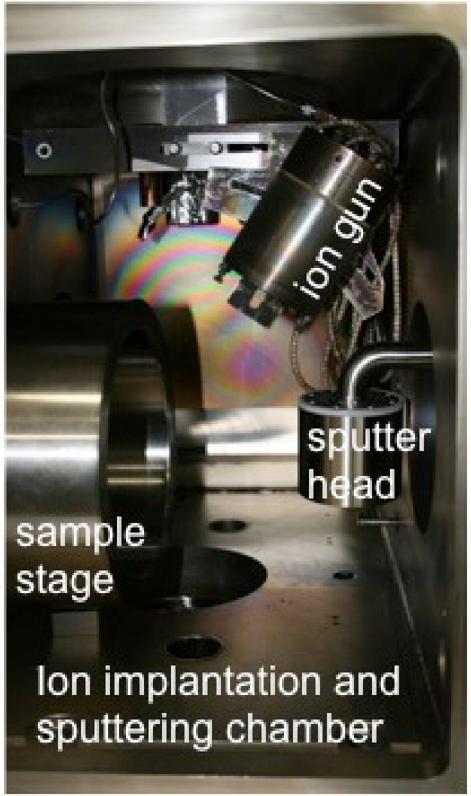
Cost modeling projections for high-volume production of dual junction $GaAs_{0.75}P_{0.25}$/Si PV on Si substrates. To get PEC material estimates in $/m², $/W is multiplied by 370W/m² (the efficiency). Modeling performed by Mike Woodhouse of NREL's Strategic Analysis group, with funding provided by the DOE SunShot Initiative, "A Manufacturing Cost Analysis Relevant to Single- and Dual-Junction Photovoltaic Cells Fabricated with III-Vs and III-Vs grown on Czochralski Silicon". Publication Number NREL/PR-6A20-60126

Details of Ion Implantation and PtRu Sputtering Surface Modification

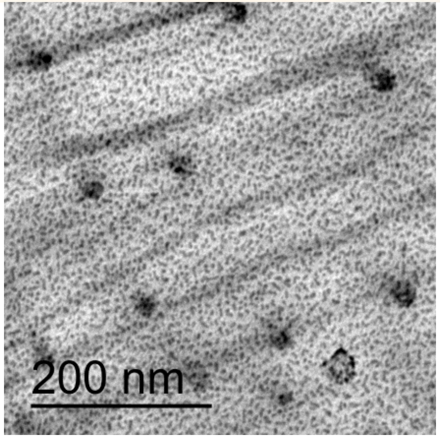
- **Rotating sample stage – 15 rpm**
- **N_2^+ ion implantation first**
  - Key parameters: Angle (55°), distance (20 cm), pressure ($8x10^{-4}$ N_2), beam voltage (550 V), beam current (12 mA)
  - Rotated 9 min through ion source (exposed 30 s)
- **PtRu alloy sputtering second**
  - Two passes through sputter plume (exposed < 0.5 s)

PtRu morphology & loading

- **Scanning transmission electron microscopy**
  - ~ 5 nm particles with approximately 30% surface coverage
- **Inductively coupled plasma mass spectrometry**
  - Several samples digested in aqua regia, diluted solutions analyzed for PtRu
  - Equivalent coverage (assuming a continuous thin film) is between 1-2 nm
    - Adds $\$2/m^2$ to absorber costs
    - Requires 66 g of Pt for a 1000 kg/day type 4 reactor array using ultimate DOE targets (25% STH, 15x concentration)



Ion implantation and sputtering chamber



Simulating AM 1.5 G Solar Spectrum