Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Project ID p161

Protective Catalyst Systems on III-V and Si-based Semiconductors for Efficient, Durable Photoelectrochemical Water Splitting Devices

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May 20th, 2020

2020 DOE Hydrogen and Fuel Cells Annual Merit Review

NREL BERKELEY LAB Sandia National Laboratories INL Idaho National Laboratory Lawrence Livermore National Laboratory SRNL

Project Overview

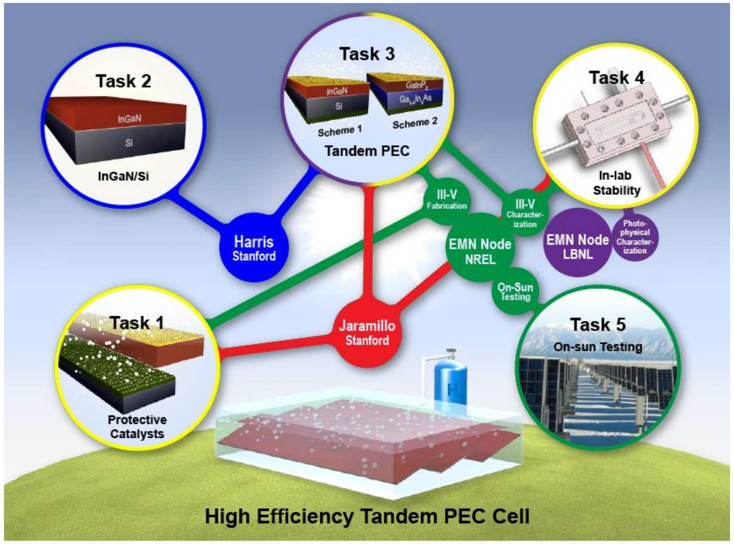
Project Partners

PI: Thomas Jaramillo, Stanford University
Co-PI, James Harris, Stanford University

Award #	EE0008084
Start/End Date	10/01/2017 – 09/30/2020
Total Project Value* Cost Share %	$750,000 10%

Project Vision

We are developing unassisted water splitting devices based on III-V materials coupled with protective, non-precious metal catalyst coatings, creating pathways to improve efficiency, durability, and cost.



Project Impact

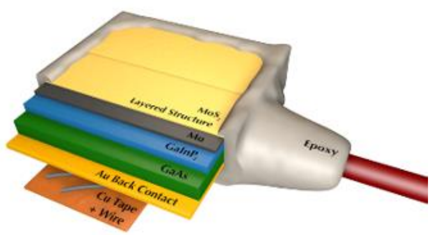
This research aims to develop unassisted water splitting devices that can achieve >20% solar-to-hydrogen (STH) efficiency, operate on-sun for at least 2 weeks, and provide a path toward electrodes that cost $\$200/m^2$.

** this amount does not cover support for HydroGEN resources leveraged by the project (which is provided separately by DOE)*

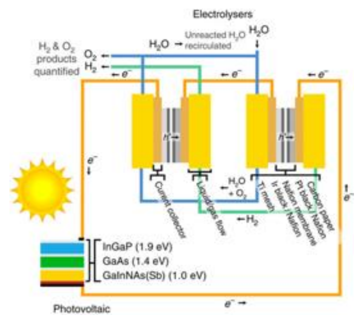
Approach: Summary

Project Motivation

We seek to combine the expertise in electrocatalysis and protective layer development of the Jaramillo group with the semiconductor growth capabilities of the Harris group and III-V fabrication knowledge at NREL. These synergies give a path towards efficient and durable III-V/III-V and III-V/Si PEC Devices.



Reuben J. Britto, et. al. *J. Phys. Chem. Lett.* **2016** 7 (11), 2044-2049



Jia, J. et al. *Nat. Commun.* **7**, 13237

Key Impact

Metric	State of the Art	Expected Advance
PEC STH (III-V)	*19% Young, J. L. et al. Nat. Energy 2017, 2, 17028.*	*>20%*
PEC Stability (III-V)	*100 h indoor – GaAs/GaInP Sun, K. et al. Adv Energy Mater 2016, 6(13), 1600379*	*2 weeks on-sun*
Si/III-V Tandem	Si-InGaN nanowire synthesis *Wang, Y. et al. Nano Energy*, **2019**, *57*, 405-413.	epitaxial growth InGaN on Si

Barriers

AF – Materials Durability – Bulk and Interface

Stabilization of unstable III-V surfaces in acid using MoS_2 and other non-precious metal protecting/catalytic layers

AE – Materials Efficiency – Bulk and Interaface

Develop fabrication of crystalline InGaN on Si by MOCVD to lead to a high efficiency tandem absorber

AK – Diurnal Operation Limitations

Develop outdoor test setup and conduct on-sun testing of stabilized III-V unassisted water splitting devices

Partners

Jaramillo Group

Electrochemistry, catalysis, protective layer expertise (characterization, catalyst deposition)

Harris Group

Semiconductor expertise, particularly in novel synthesis, processing, and fabrication techniques (InGaN growth)

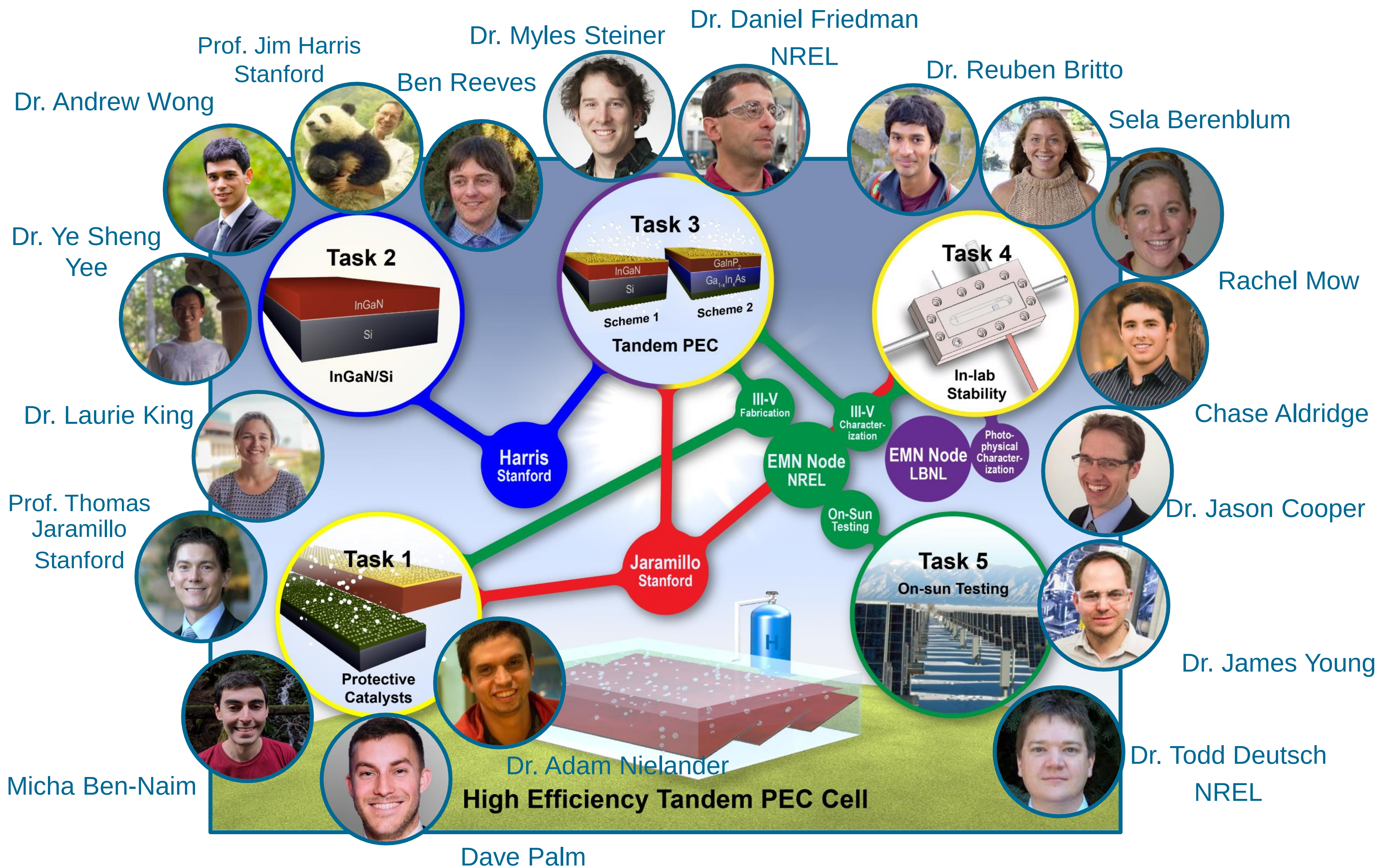
NREL

III-V fabrication (epitaxial growth) expertise, on-sun testing expertise, unassisted water splitting device expertise

LBNL

In Situ Photoelectrochemical Raman spectroscopy

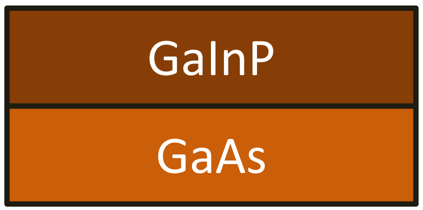
Approach: The team



Approach: Innovation

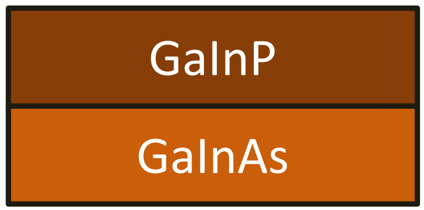
Scheme 1
III/V-III/V

a. Upright Tandem



- Robust fabrication
- Prior success protecting in acid

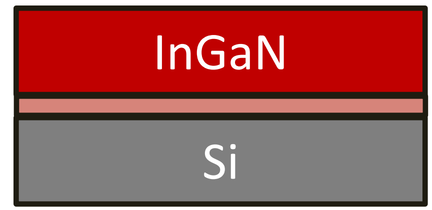
b. IMM/High Efficiency Tandem



- Higher efficiency
- Novel semiconductor fabrication

- Most direct pathway to high efficiency devices

Scheme 2
III/V-Si



- New fabrication approaches – growth of crystalline InGaN on Si is a challenge in the field
- Pathway to cheaper fabrication
- Prior success growing LEDs

End of Project Goal #1

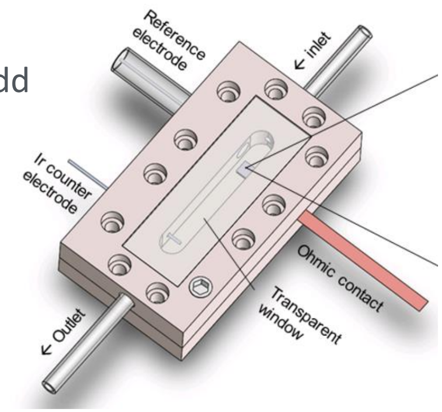
On-sun testing of unassisted water splitting devices for ≥ 2 weeks.

End of Project Goal #2

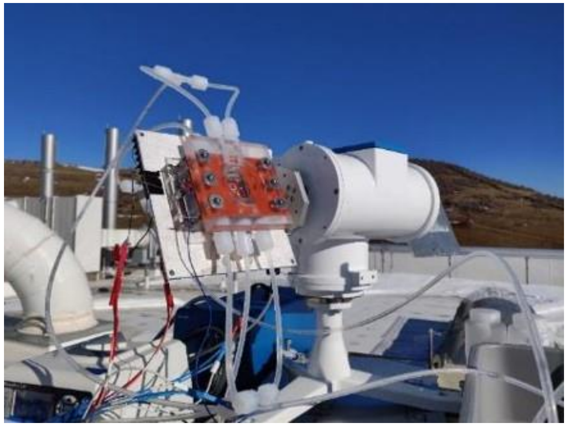
Demonstration of an unassisted water splitting device with ≥ 20% STH efficiency.

Approach: Innovation

- **Stabilization of III-V surfaces in acid**
  - **Innovation:** Use MoS_2 and other non-precious protective catalysts that are stable in acid, conductive, and active for HER. Developing an understanding of fundamental degradation mechanisms through *in situ* studies and leverage those insights into better protective catalysts
    - **Task 1:** Translatable, thin-film catalyst and protection layer development
    - **Task 3:** III-V fabrication and PEC device development for tandem III-V and InGaN/Si
    - **Task 4:** In-situ stability studies
  - **EMN Nodes:** i) Characterization of Semiconductor Bulk and Interfacial Properties (Todd Deutsch, NREL), ii) Corrosion Analysis of Materials (Todd Deutsch, NREL), and iii) III-V Semiconductor Epi-structure and Device Design and Fabrication (Daniel Friedman, NREL).



- **Fabrication scheme for high-quality InGaN growth on Si**
  - **Innovation:** First demonstration of direct nucleation and growth of InGaN on monocrystalline Si by MOCVD in this field.
    - **Task 2:** Tandem InGaN/Si fabrication



- **Collecting on-sun data at the weeks time-scale**
  - **Innovation:** By stabilizing III-V unassisted water splitting devices for 100's of hours, we can test them outside for weeks
    - **Task 5:** On-sun testing at NREL
  - **EMN Nodes:** On-Sun Solar-to-Hydrogen Benchmarking (Todd Deutsch, NREL)

Approach: Budget Period 2 Milestones

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
2.0	**Task 2: Tandem InGaN/Si fabrication**			
2.4	Demonstrate working tandem InGaN/Si solar cell device	5/31/19	70%	Working InGaN solar cell
2.5	Demonstrate a tandem InGaN/Si solar cell with power conversion efficiencies of > 10%	12/31/19	30%	InGaN/Si solar cell with Si photovoltaic material
3.0	**Task 3: III-V fabrication and PEC device development for tandem III-V and InGaN/Si**			
3.2	Demonstrate InGaN/Si tandem absorbers that produce hydrogen during light-driven, unassisted water splitting	9/30/19	40%	Photoanode behavior by MOCVD-grown InGaN with NiO hole-transport layer
3.3	3.3.1: Demonstrate InGaN/Si as a photoelectrode for unassisted water splitting with >1% STH 3.3.2: Design and implement improved dual III-V tandem absorbers which achieve STH efficiency >15%	3/31/20	0% 75%	12.8% STH with IMM tandem $GaInP_2$/GaInAs
3.4	3.4.1: Demonstrate unassisted water splitting device with >20% STH efficiency that maintains at least 10% STH efficiency for >100 h. 3.4.2: Demonstrate unassisted water splitting using InGaN/Si with >2% initial STH that continues to produce hydrogen after >100 hrs of continuous illumination	9/30/20	0% 0%	
4.0	**Task 4: In-Lab Stability Studies**			
4.2	Utilize the flow cell for analyzing the degradation mechanisms of the III-V based tandem PEC devices.	9/30/20	25%	PEC testing in flow cell and ex-situ Raman spectroscopy
5.0	**Task 5: On-sun testing**			
5.1	5.1.1: Finalize the outdoor PEC cell setup, design and protocols to enable on-sun data collection for >24 hours 5.1.12: Collect >10 mL of hydrogen from an unassisted water splitting device in an on-sun testing in one day	12/31/19	100%	Generated 14.4 mL of hydrogen during on-sun test on 1/15/20
5.2	Demonstrate photoelectrode that generates hydrogen under diurnal conditions on-sun for greater than or equal to 2 weeks	9/30/20	0%	
End of Project Goal	**On-sun testing of Scheme 1 and 2 unassisted water splitting devices for >2 weeks. Demonstration of an unassisted water splitting device with an average greater than 20% STH efficiency.**	**9/30/20**	**20%** **30%**	One-day of on-sun testing 12.8% STH with IMM tandem

Relevance & Impact

This project advances towards <$2/kg hydrogen by:

- Improving efficiency and durability of state-of-the-art photoelectrodes using earth-abundant protection layers towards > 20% solar-to-hydrogen (STH) efficiency with long-term, on-sun operation

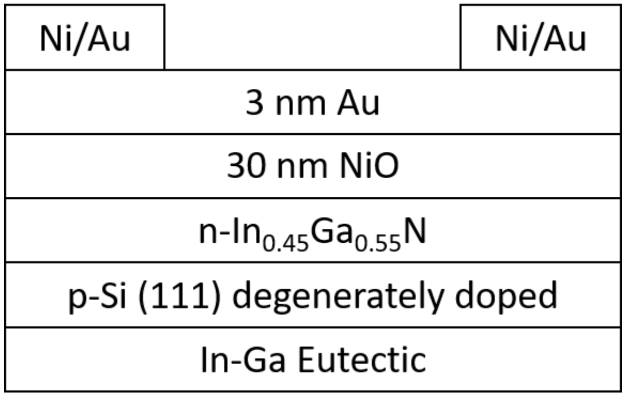
Leveraging EMN Resource Nodes:

- **NREL EMN Node: Characterization of Semiconductor Bulk and Interfacial Properties, Todd Deutsch,**
  - Characterization of fundamental semiconductor properties and growth defects before and after testing
- **NREL EMN Node: Corrosion Analysis of Materials, Todd Deutsch,**
  - Pre- and post- failure analysis and improved understanding of catalyst corrosion and interface energetics
- **NREL EMN Node: III-V Semiconductor Epi-structure and Device Design and Fabrication, Daniel Friedman,**
  - Fabrication of III-V materials and systems and improved understanding of growth defects
- **NREL EMN Node: On-Sun Solar-to-Hydrogen Benchmarking, Todd Deutsch,**
  - Testing station for collection of on-sun data for unassisted water splitting devices
- **LBNL EMN Node: Photophysical Characterization of Photoelectrochemical Materials and Assemblies, Jason Cooper**
  - *In Situ* Photoelectrochemical Raman spectroscopy to identify degradation pathways

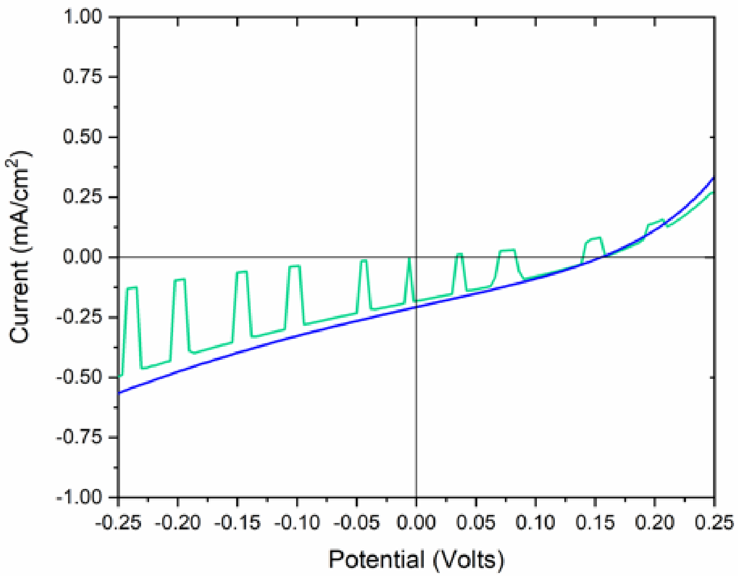
Jaramillo group has worked with multiple EMN nodes to successfully protect III-V photocathodes in acid with collaboration track record spanning the last 6 years, resulting in published work and improved node capabilities

Accomplishments for Task 2: InGaN/Si Fabrication

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
2.4	Demonstrate working tandem InGaN/Si solar cell device	5/31/19	70%	Working InGaN solar cell
2.5	Demonstrate a tandem InGaN/Si solar cell with power conversion efficiencies of > 10%	12/31/19	30%	InGaN/Si solar cell with Si photovoltaic material



Device structure with InGaN, a NiO hole transport layer and Au top contact.

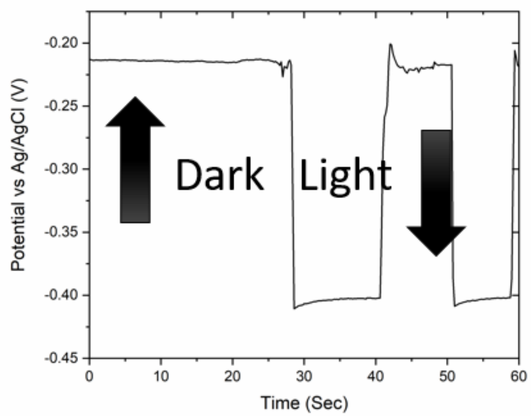


Illuminated JV Characteristic under 1-sun condition (blue) and chopped illumination (green)

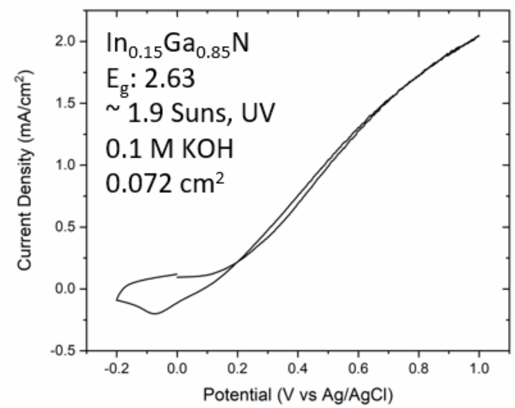
InGaN with a NiO hole transport layer acts as a functioning photovoltaic, producing up to 0.3 mA/cm^2 of photocurrent

Accomplishments for Task 3: Stable Unassisted Water Splitting

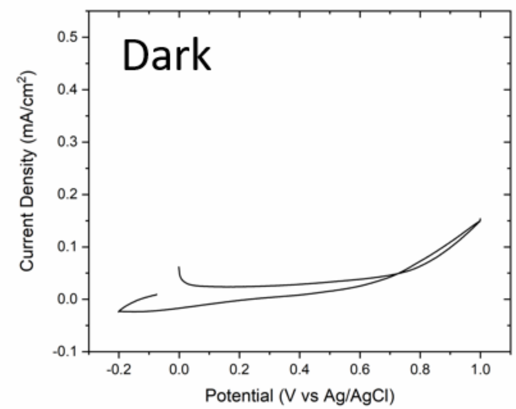
Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
3.2	Demonstrate InGaN/Si tandem absorbers that produce hydrogen during light-driven, unassisted water splitting	9/30/19	40%	Photoanode behavior by MOCVD-grown InGaN with NiO hole-transport layer



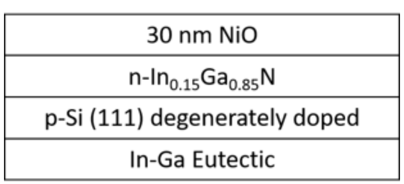
Open circuit potential in the dark and light showing a photoanode response



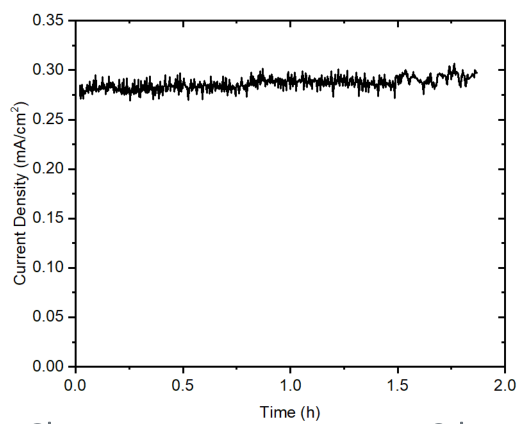
Illuminated JV Characteristic under 2 sun illumination



Dark JV characteristic showing minimal dark current



Device structure with InGaN and NiO hole transport layer

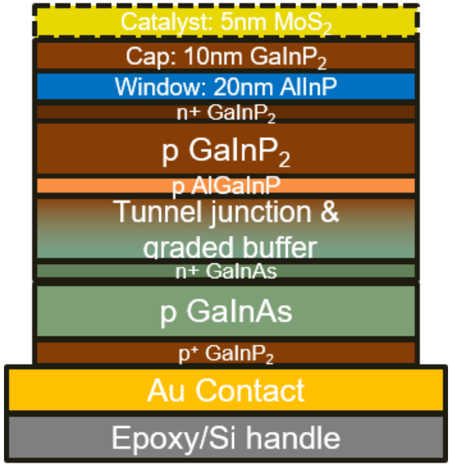


Chronoamperometry over 2 hours at 1.23 V vs. RHE

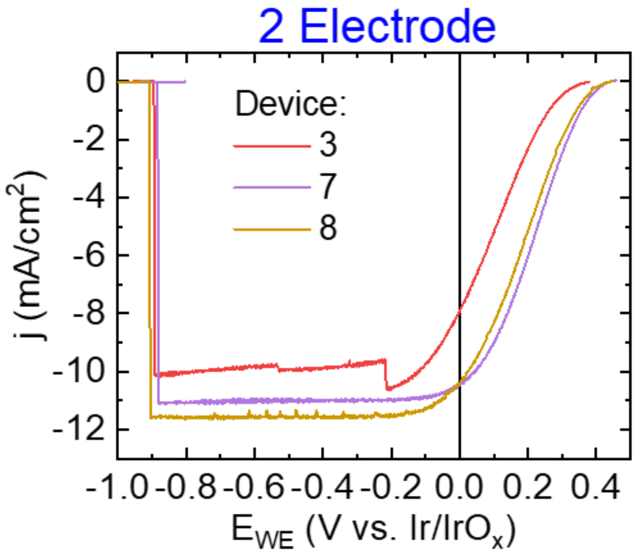
InGaN with a NiO hole transport layer acts as a photoanode, with up to 1.8 mA cm^{-2} of photocurrent under 2 suns illumination in KOH electrolyte

Accomplishments for Task 3: Stable Unassisted Water Splitting

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
3.3	3.3.2: Design and implement improved dual III-V tandem absorbers which achieve STH efficiency >15%	3/31/20	75%	12.8% STH with IMM tandem $GaInP_2$/GaInAs



Device structure for IMM tandem of $GaInP_2$ and GaInAs with a window layer, capping layer, and MoS_2 catalyst



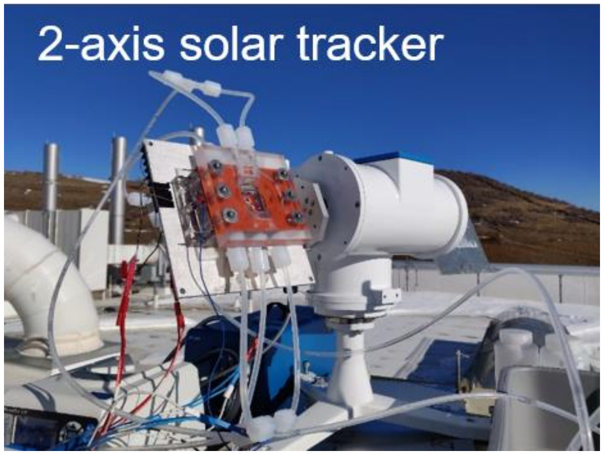
9 devices were made from the same growth. Two-electrode LSV are shown for one lower-performance device (3) and the two highest-performance cells (7,8)

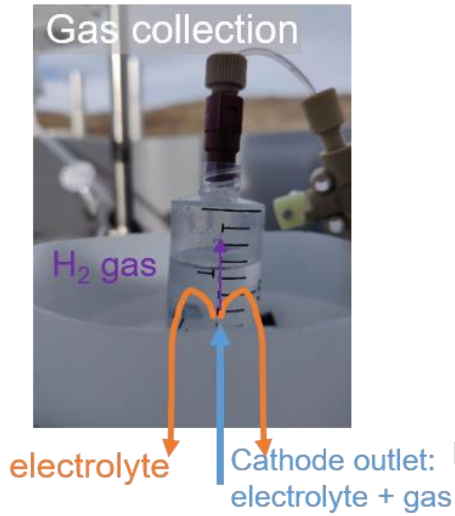
An Inverted Metamorphic Multijunction (IMM) tandem of $GaInP_2$ and GaInAs (1.8/1.18 eV) demonstrated an STH efficiency of 12.8%

Nodes Utilized:
Characterization of Semiconductor Bulk and Interfacial Properties
III-V Semiconductor Epi-structure and Device Design and Fabrication
Corrosion Analysis of Materials

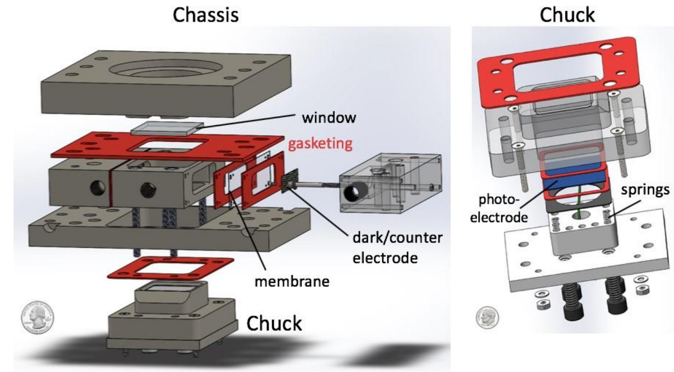
Accomplishments for Task 5: On-sun Stability Studies

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.1: Finalize the outdoor PEC cell setup, design and protocols to enable on-sun data collection for >24 hours	12/31/19	100%	Developed photoreactor and testing protocol





Photoreactor setup on a 2 axis solar tracker including gas collection syringe.



https://www.h2awsm.org/capabilities/sun-photoelectrochemical-solar-hydrogen-benchmarking

Photoreactor chassis and chuck schematic

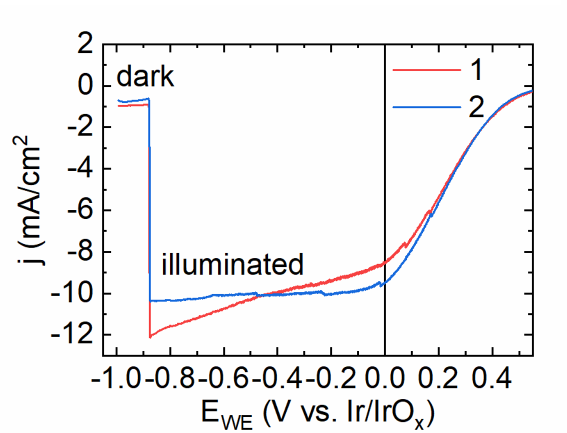
In collaboration with the On-sun EMN node at NREL, we developed a cell and protocol for outdoor testing on the NREL ESIF rooftop.

Stanford PhD student Micha Ben-Naim travelled to NREL in Dec 2019 to conduct on-sun testing.

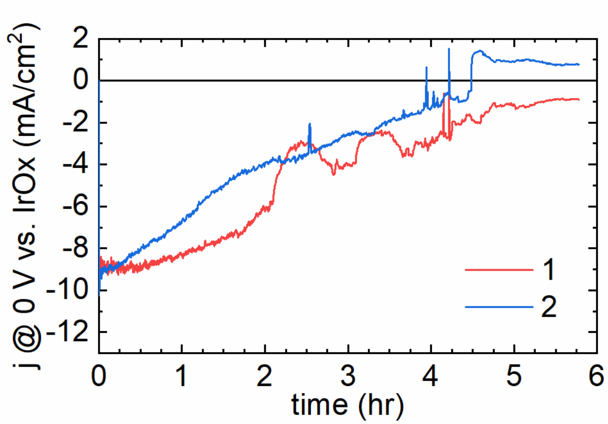
Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking

Accomplishments for Task 5: On-sun Stability Studies

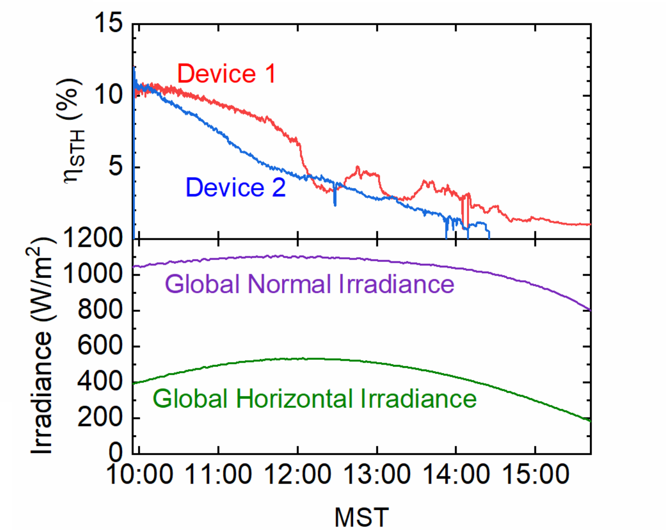
Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.12: Collect >10 mL of hydrogen from an unassisted water splitting device in an on-sun testing in one day	12/31/19	100%	Generated 14.4 mL of hydrogen during on-sun test



2 electrode LSV measured on-sun showing unassisted water-splitting capability



Chronoamperometry measured on-sun over 6 hours at short circuit



STH efficiency over time (top) accounting for variable sunlight (bottom)

On-sun testing of a $GaInP_2$/GaAs tandem (1.8/1.4 eV) protected by MoS_2 generated 14.4 mL of hydrogen on 1/15/20

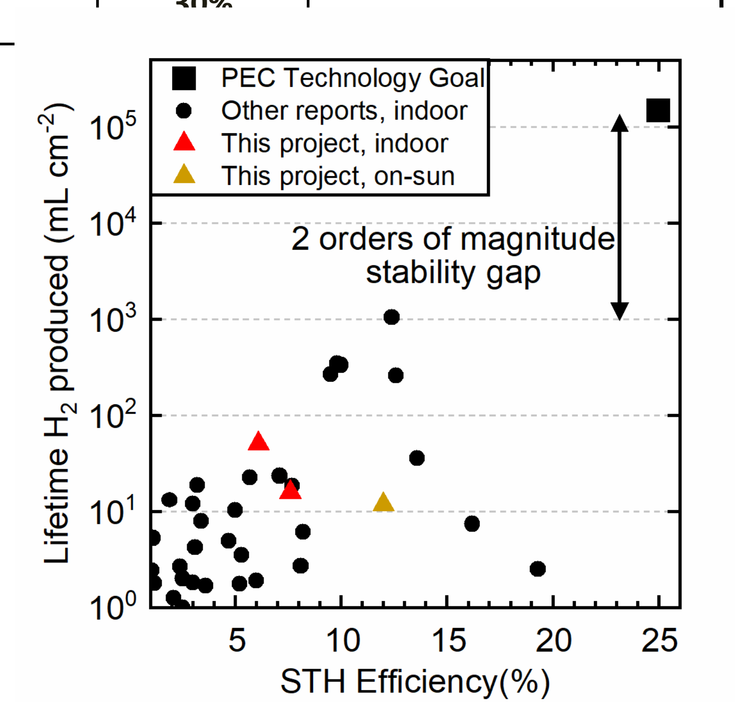
Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking

Accomplishments: Outlook for future and End of Project Goals

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
End of Project Goal	On-sun testing of Scheme 1 and 2 unassisted water splitting devices for >2 weeks.	9/30/20	20%	14.4 mL hydrogen generated in 1 day on-sun
	Demonstration of an unassisted water splitting device with an average greater than 20% STH efficiency.		30%	Unassisted water-splitting

These end of project goals would push both the stability and efficiency records in the field of PEC water-splitting. Outdoor testing would provide new insights into real-world operating conditions.

We are excited to demonstrate on-sun testing at the weeks timescale as a demonstration of stable PEC hydrogen production.



Summary of unassisted PEC water-splitting devices in the field comparing efficiency (STH) and durability by lifetime H_2 produced

Collaboration: EMN

▸ NREL: Characterization of Semiconductor Bulk and Interfacial Properties, ***Todd Deutsch*** ▸ NREL: Corrosion Analysis of Materials, ***Judith Vidal, Todd Deutsch, James Young*** – Pre- and post- characterization and failure analysis of photocathodes and unassisted water splitting devices	Worked with to analyze our photoelectrodes before and after testing to determine failure mechanisms and strategies for improvement.
▸ NREL: III-V Semiconductor Epi-structure and Device Design and Fabrication, ***Daniel Friedman*** – Design and fabrication of III-V materials and systems	Worked with to fabricate high-quality absorbers compatible with our catalytic protection layers.
▸ NREL: On-Sun Solar-to-Hydrogen Benchmarking, ***Todd Deutsch*** – Testing station for collection of on-sun data for unassisted water splitting devices	Worked with to design our electrodes to be compatible with NREL's on-sun testing setup. Stanford student was on-site in December 2019 to perform on-sun testing, with future experiments planned.
▸ LBNL: Photophysical Characterization of Photoelectrochemical Materials and Assemblies, ***Jason Cooper*** – *In Situ* photoelectrochemical Raman Spectroscopy	Worked with to conduct in-lab stability studies

Collaboration: EMN and beyond

- **EMN Collaboration**
  - Weekly videochats between Stanford (Micha Ben-Naim) and NREL (James Young, Chase Aldridge, Myles Steiner)
  - Weekly exchange of samples fabricated at NREL and further processed at Stanford
  - Parallel photoelectrochemical testing and characterization of samples at Stanford and NREL to ensure accuracy and accelerate research progress
  - Weeklong site visit to NREL (Micha Ben-Naim) for on-sun testing in December 2019

- **Positive interactions with the broad HydroGEN community**
  - Kickoff meeting in November 2017 at NREL provided an opportunity to engage with the community, learn about the plethora of available tools, methods, and expertise.
  - PEC community meeting at ECS in Seattle in May 2018 to discuss HydroGEN, benchmarking, and related activities.
  - HydroGEN EMN Advanced Water Splitting Technology Pathways Benchmarking & Protocols Workshop, Tempe, AZ in October 2018 and 2019
  - Presentation to Hydrogen Production Tech Team (HPTT) in February 2019.

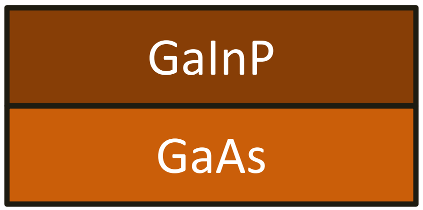
- **Incorporating project data onto the HydroGEN data hub**
  - We learned how to use the H2awsm tools at the kickoff meeting to upload our data for the broader community.
  - All of our photocathode stability data and linear sweep voltammetry data will be uploaded.
  - We hope this will help accelerate the stability benchmarking effort.

- **Collaboration with LBNL: EMN node and Molecular Foundry**
  - Started working with Dr. Jason Cooper and the photophysical characterization node for in-lab stability efforts.
  - Worked with Dr. Jason Cooper at LBNL to write a successful Molecular Foundry user proposal to use ALD to deposit MoS_2 on III-V materials for improved PEC stability.

Proposed Future Work

Scheme 1
III/V-III/V

a. Upright Tandem



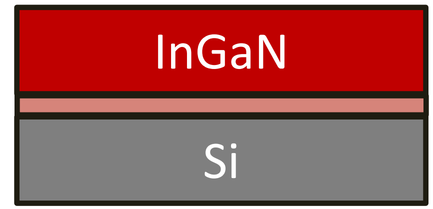
- High durability to allow for additional on-sun testing

b. IMM/High Efficiency Tandem

- Target high efficiency systems

- Continue fabrication and regular sample exchanges between Stanford & NREL, coat with MoS_2
- Additional on-sun testing planned

Scheme 2
III/V-Si



- Continue to develop InGaN/Si growth by MOCVD
- Build upon photoanode behavior to develop tandem PEC systems

End of Project Goal #1

On-sun testing of unassisted water splitting devices for ≥ 2 weeks.

Proposed Budget: $53k

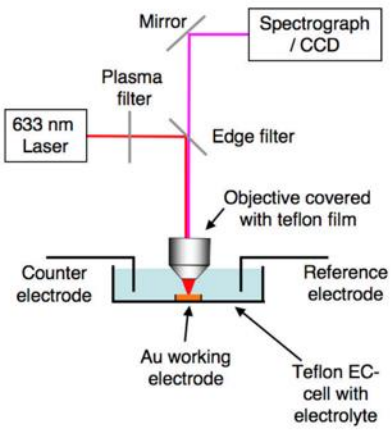
End of Project Goal #2

Demonstration of an unassisted water splitting device with ≥ 20% STH efficiency.

Any proposed future work is subject to change based on funding levels

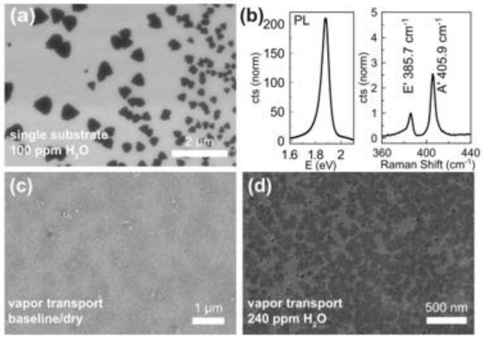
Proposed Future Work

In Situ Spectroscopy



- Work with the Photophysical Characterization of Photoelectrochemical Materials and Assemblies node at LBNL for *in situ* Raman studies
- Characterize degradation pathways to improve device longevity

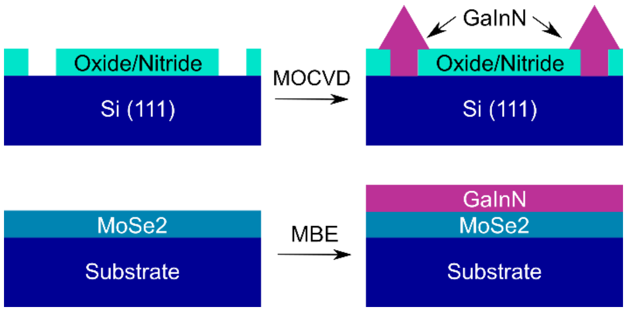
Improved MoS_2 Layers



Kastl, C. et al., *2D Mater.* **2017**, *4*, 021024

- Utilize ALD + H_2S anneal to deposit thinner and more uniform layers of MoS_2
- Collaborate with Molecular Foundry at LBNL
- Improve device stability to enable testing outside for ≥ 2 weeks

InGaN Fabrication



- Reduce GaInN crystalline defects using different epitaxial growth techniques
- MOCVD on oxide/nitride-patterned Si (111) templates
- Molecular beam epitaxy on lattice-matched transition metal dichalcogenides

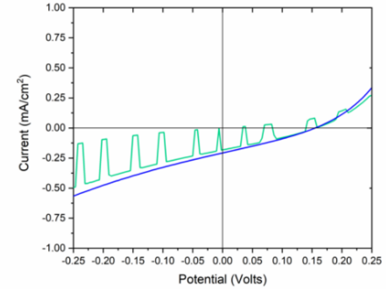
Proposed Budget: $53k

Any proposed future work is subject to change based on funding levels

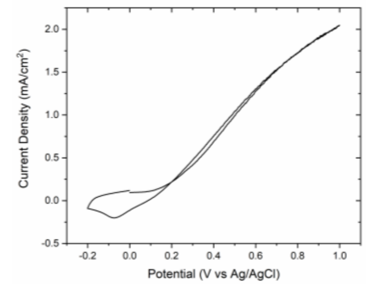
Project Summary

Task 2 – High Quality InGaN on Si

- Photovoltaic characteristics by $In_{0.45}Ga_{0.55}N$ on Si (111) using MOCVD

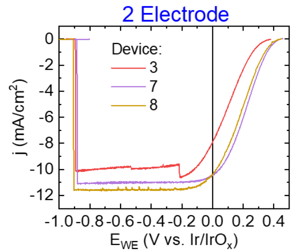


- Photoanode behavior by $In_{0.45}Ga_{0.55}N$ on Si (111) using MOCVD



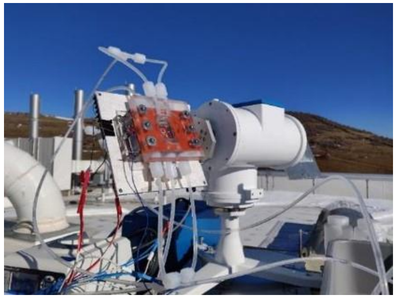
Task 3 – Stable Unassisted Water Splitting

- IMM tandem ($GaInP_2$/GaInAs) protected with MoS_2 generated 12.8% STH

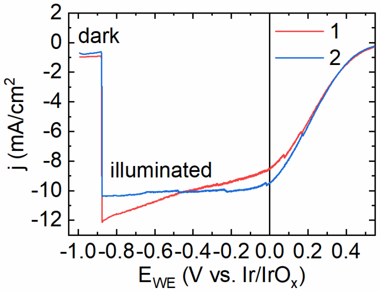


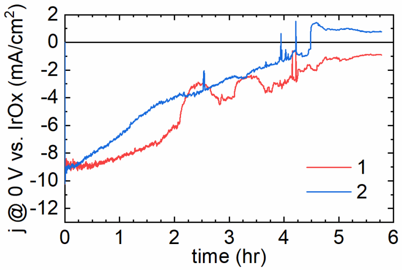
Task 5 – On-sun Stability Studies

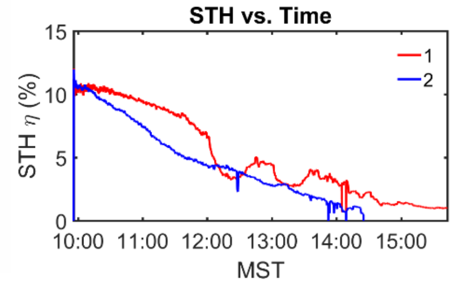
- Development of on-sun testing photoreactor and test protocols



- Successful on-sun hydrogen generation on 12/7/19, 12/20/19, and 1/15/20, generating up to 14.4 mL H_2 in a day







We have demonstrated on-sun hydrogen generation from an unassisted water-splitting device with >10% STH

Publications and Presentations

Publications and Manuscripts in preparation

- *Interfacial Engineering of Gallium Indium Phosphide Photoelectrodes for Hydrogen Evolution with Precious Metal and Non-Precious Metal Based Catalysts.* Reuben J. Britto, James L. Young, Ye Yang, Myles A. Steiner, David T. LaFehr, Mathew Beard, Todd G. Deutsch, Thomas F. Jaramillo. *Journal of Materials Chemistry A*, **2019**, *7*, 16821-16832
- *Transition Metal Arsenide Catalysts for the Hydrogen Evolution Reaction.* Joseph A. Gauthier, Laurie A. King, Faith Tucker Stults, Raul A. Flores, Jakob Kibsgaard, Yagya N. Regmi, Karen Chan, Thomas F. Jaramillo. *Journal of Physical Chemistry C* **2019**, *123* (39), 24007-24012
- *Overcoming the Stability Gap in Photoelectrochemistry: Molybdenum Disulfide Protective Catalysts for Tandem III-V Unassisted Solar Water Splitting.* Micha Ben-Naim*, Reuben J. Britto*, Chase Aldridge, Rachel Mow, Myles A. Steiner, Adam C. Nielander, Laurie A. King, Daniel J. Friedman, Todd G. Deutsch, James L. Young, Thomas F. Jaramillo. **2020**, *Under Review*
- *Epitaxial Growth of InGaN Directly on Si (111) via MOCVD: Properties and Junction Characteristics.* Andrew B. Wong*, Yesheng Yee*, Laurie King, Muyu Xue, Thomas F. Jaramillo, James S. Harris. *In Prep*
- *Photovoltaic Properties of InGaN/Si Heterojunction Tandem Cells.* Andrew B. Wong, Yesheng Yee, Laurie King, Muyu Xue, Thomas F. Jaramillo, James S. Harris. *In Prep*

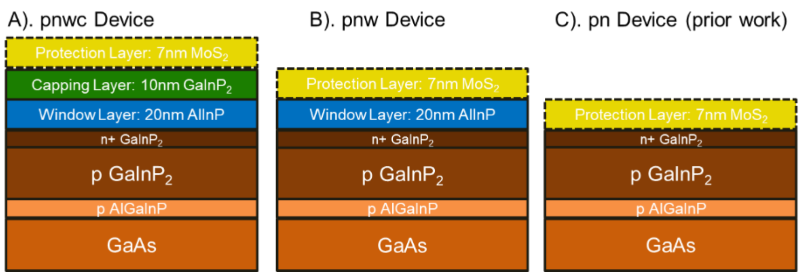
Presentations

- (Invited) 2020 NCCC, The Netherlands' Catalysis and Chemistry Conference, Noordwijkerhout, Netherlands. “Catalyst development for the sustainable production of fuels and chemicals,” T.F. Jaramillo, March 2020.
- 2019 Materials Research Society Fall Meeting in Boston, MA, “InGaN-Si Tandem Photoelectrodes for Photoelectrochemical Water Splitting by MOCVD—Understanding System Design Considerations Necessary to Bridge Theory and Experiment”, A.B. Wong, December 2019.
- (Invited) Chemical Sciences Roundtable, Advances, Challenges, and Long-Term Opportunities of Electrochemistry: Addressing Societal Needs, National Academies of Sciences, Engineering, and Medicine, Washington, D.C. “Designing new catalysts and processes for the sustainable production of fuels and chemicals,” T.F. Jaramillo, November 2019.
- (Invited) Department of Chemical and Biomolecular Engineering, Rice University, Houston, TX. “Catalyst design and development for sustainable fuels and chemicals,” T.F. Jaramillo, October 2019.
- (Invited) 236th Meeting of The Electrochemical Society (ECS), Atlanta, GA. “Materials Discovery and Development for the Sustainable Production of Fuels and Chemicals,” T.F. Jaramillo, October 2019.
- (Invited) 2019 Materials Research Society Spring Meeting in Phoenix, AZ, “Development of Catalytic Coatings for H_2-Producing Photocathodes in Solar Water-Splitting”, T.F. Jaramillo, April 2019.

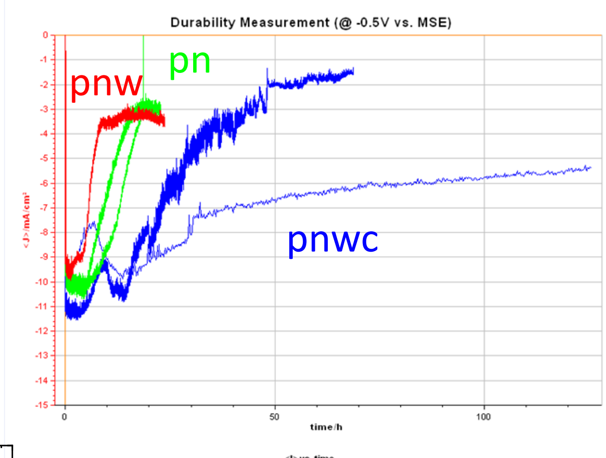
Technical Backup Slides

Backup Slide 1: New semiconductor architecture accomplishments

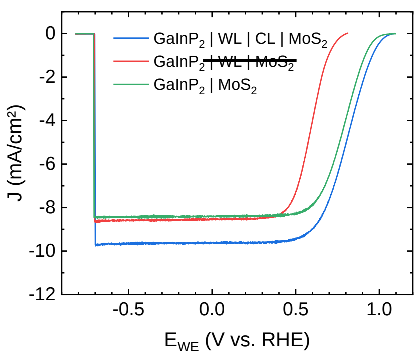
Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
3.3	3.3.2: Design and implement improved dual III-V tandem absorbers which achieve STH efficiency >15%	3/31/20	75%	12.8% STH with IMM tandem $GaInP_2$/GaInAs



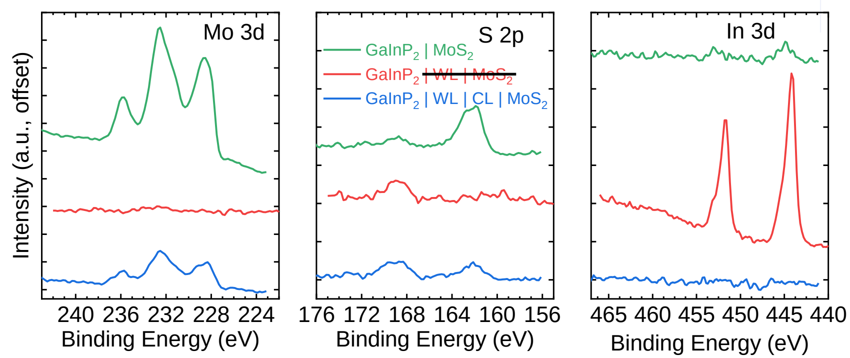
Device stacks tested with window and capping layers on pn-$GaInP_2$



Durability test of three photocathodes.



J-V characteristics of three photocathodes



Post-test XPS showing that the window layer alone is unstable

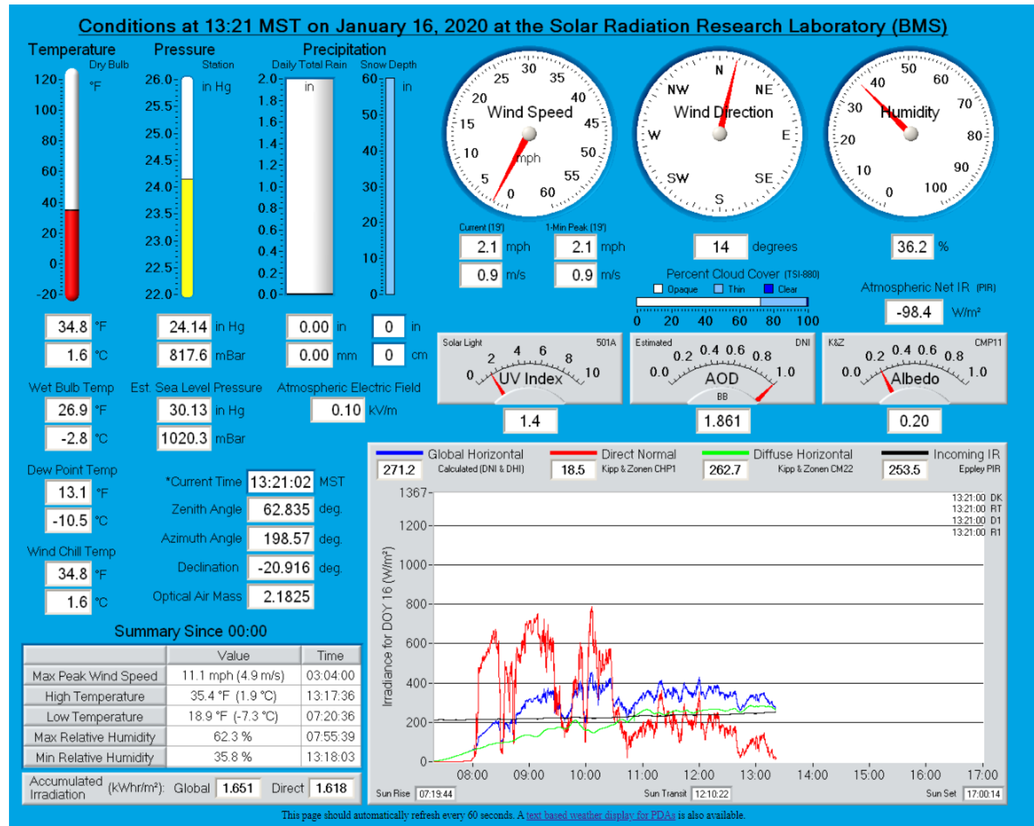
The addition of a window and capping layer improve photocathode efficiency and stability. This architecture was translated to the top cell of scheme 1 tandems

Backup Slide 2: On-sun Testing Accomplishments

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.1: Finalize the outdoor PEC cell setup, design and protocols to enable on-sun data collection for >24 hours	12/31/19	100%	Developed photoreactor and testing protocol

SRRL Instrummentation

Solar Research Radiation Laboratory (SRRL) at NREL provides > 80 environmental and irradiance monitoring equipment 0.5 mi from PEC test setup

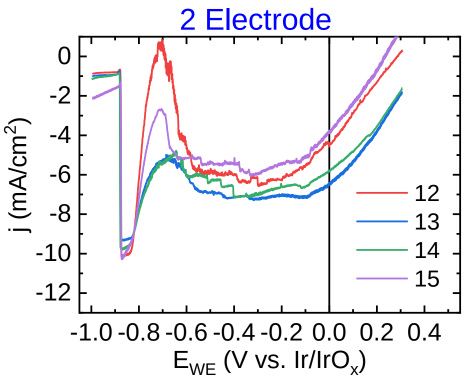


Dashboard with real-time data collected by SRRL
https://midcdmz.nrel.gov/apps/gdisplay.pl?BMS

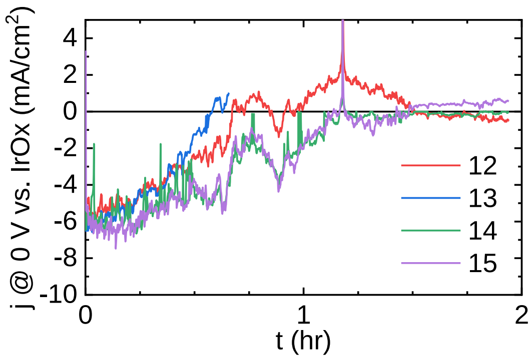
Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking

Backup Slide 3: On-sun Testing Accomplishments 12/7/19

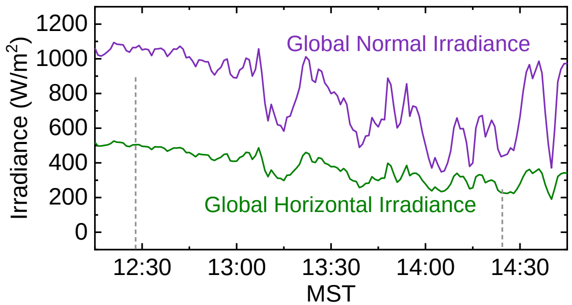
Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.12: Collect >10 mL of hydrogen from an unassisted water splitting device in an on-sun testing in one day	12/31/19	100%	Generated 14.4 mL of hydrogen during on-sun test



2 electrode LSV measured on-sun showing unassisted water-splitting capability



Chronoamperometry measured on-sun over 2 hours at short circuit



Sunlight profile during partially cloudy day on 12/7/19

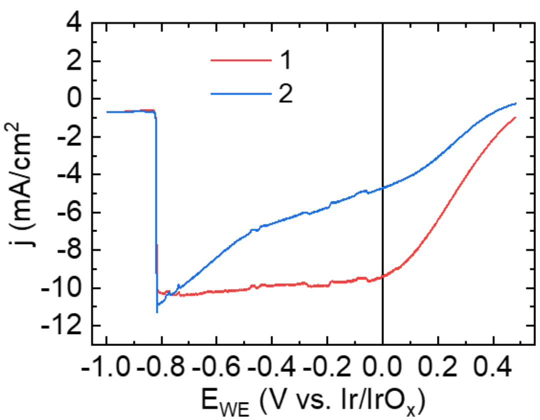
On-sun testing of a $GaInP_2$/GaAs tandem (1.8/1.4 eV) protected by MoS_2 generated 1.8 mL of hydrogen on 12/7/19, but electrodes had degraded from previous day

Gas collection tank at the end of testing

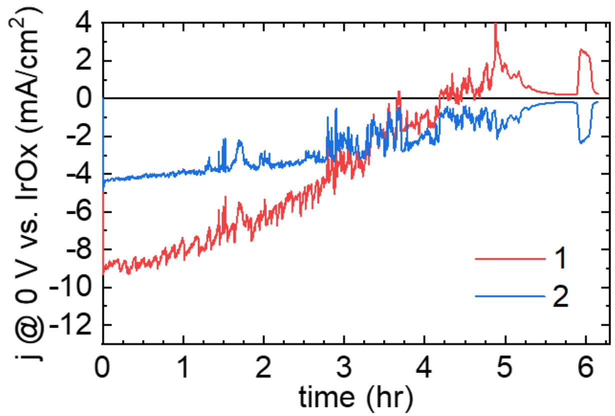
Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking

Backup Slide 4: On-sun Testing Accomplishments 12/20/19

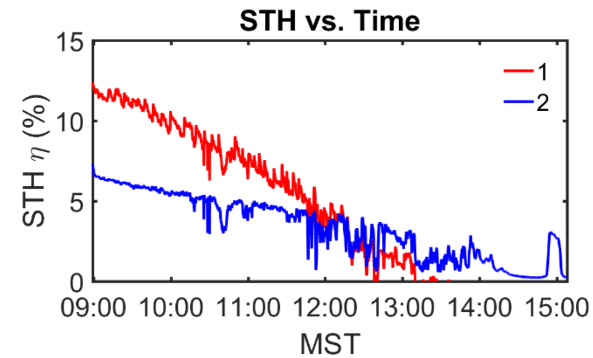
Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.12: Collect >10 mL of hydrogen from an unassisted water splitting device in an on-sun testing in one day	12/31/19	100%	Generated 14.4 mL of hydrogen during on-sun test



2 electrode LSV measured on-sun showing unassisted water-splitting capability



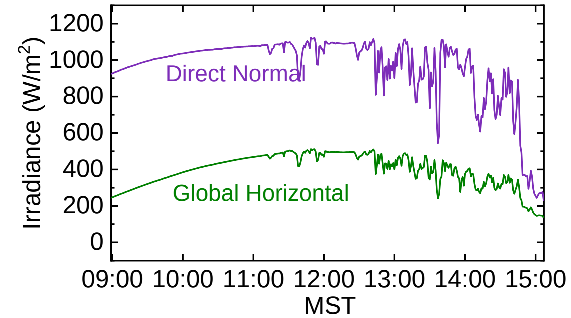
Chronoamperometry measured on-sun over 6 hours at short circuit



STH efficiency over time accounting for variable sunlight (below)

On-sun testing of a $GaInP_2$/GaAs tandem (1.8/1.4 eV) protected by MoS_2 generated 11.3 mL of hydrogen on 12/20/19

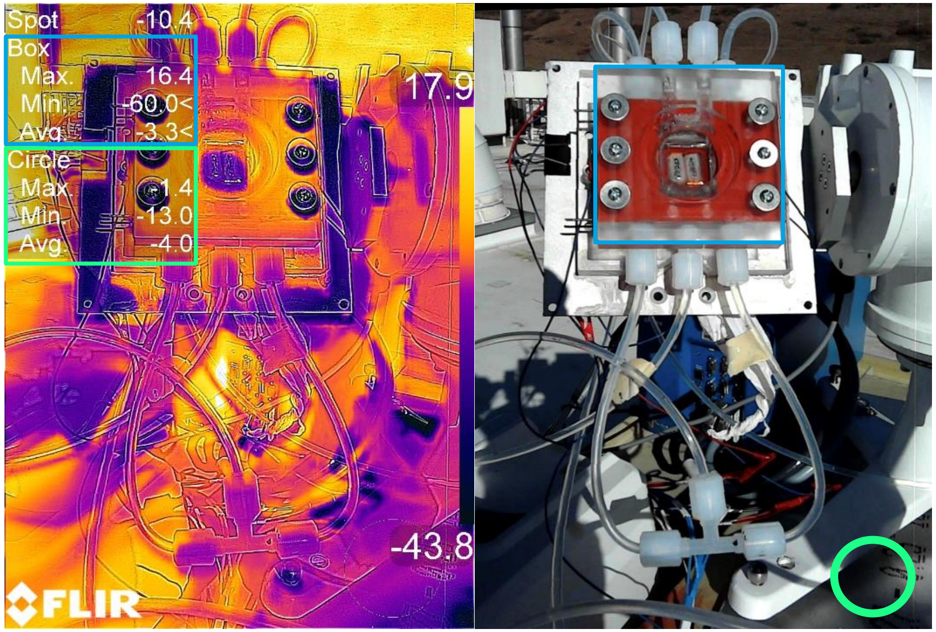
- 76 C cathodic current = 11.3 mL H_2
- Collected 10.2 mL gas (10.0 mL subtracting out water vapor pressure)



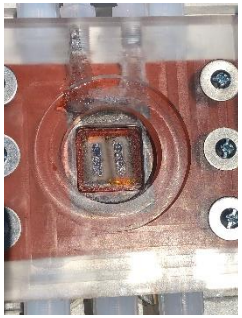
Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking

Backup Slide 5: On-sun Testing Accomplishments

Milestone	Project Milestones	Completion Date	Percent Complete	Progress Notes
5.1	5.1.12: Collect >10 mL of hydrogen from an unassisted water splitting device in an on-sun testing in one day	12/31/19	100%	Generated 14.4 mL of hydrogen during on-sun test

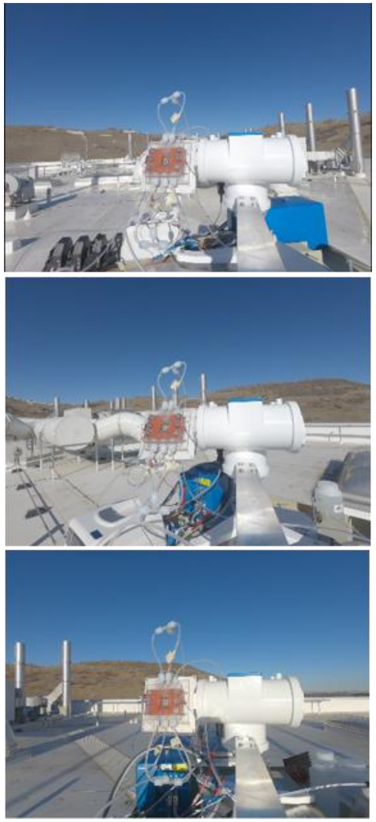


Thermal IR camera image of photoreactor during testing on 1/20/20. T_{air} ~ 4 °C



Photoreactor chuck showing two devices run in parallel

Photoreactor platform allows for a variety of supplementary datasets



Timelapse pictures of solar tracker at beginning, middle, and end of test (top, middle, bottom, respectively)

Nodes Utilized:
On-Sun Solar to Hydrogen Benchmarking