HydroGEN Seedling: Monolithically Integrated Thin-Film/Silicon Tandem Photoelectrodes for High-Efficiency and Stable Photoelectrochemical Water Splitting

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Subcontractors:
- Michigan State University, East Lansing, MI
- Boston College, Boston, MA
- University of Toledo, Toledo, OH

Project Start Date: October 1, 2017
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Develop monolithically integrated Si-based tandem photoelectrodes to achieve both high solar-to-hydrogen (STH) efficiency (>15%) and long-term stability (>1,000 hours) in spontaneous water splitting systems.

Fiscal Year (FY) 2018 Objectives

- Demonstrate top photoelectrodes with energy bandgap ~1.7–2.0 eV on Si that can deliver photocurrent density >10 mA/cm^2 and open circuit potential >0.7 V under standard one-sun illumination.
- Demonstrate proof-of-concept double-junction photoelectrode on Si, with open circuit potential further enhanced by at least 0.5 V compared to the standalone top photoelectrode.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

- **Materials Durability—Bulk and Interface:** Identify intrinsically durable and efficient materials for photoelectrochemical (PEC) hydrogen generation.
- **Integrated Device Configurations:** Develop efficient, stable integrated devices to meet the ultimate targets in PEC hydrogen generation.
- **Synthesis and Manufacturing:** Scalable manufacturing of PEC materials and devices.

Technical Targets

This project is developing monolithically integrated tandem photoelectrodes on low-cost, large-area Si wafer. Success of this project will provide the materials platform for PEC water splitting devices that help meet the following DOE PEC hydrogen production targets:

- STH energy conversion ratio: 20%
- PEC electrode cost: $200/m^2.

FY 2018 Accomplishments

- Demonstrated top photoelectrode with photocurrent density >12 mA/cm^2 at 0 V vs. normal hydrogen electrode (NHE) and open circuit potential >0.75 V.
- Demonstrated InGaN/Si double-junction photocathode that can exhibit an onset potential ~2 V vs. reversible hydrogen electrode (RHE), representing an enhancement of the photovoltage by 1.5 V compared to the Si photocathode. Such a device can perform unassisted solar water splitting.
- Demonstrated that GaN/Si photocathode can exhibit stable (>100 h) and efficient operation (photocurrent density >38 mA/cm^2 under one-sun illumination) without using any extra surface protection.

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

INTRODUCTION

The DOE STH conversion efficiency and cost targets for purified, 300 psi compressed hydrogen gas are 20% STH and $5.70/kg hydrogen by 2020. The tandem PEC device concept of stacking wide-bandgap and narrow-bandgap semiconductors is a proven method that can achieve the targeted STH efficiency. To date, all efficient tandem PEC devices are based on the state-of-the-art III-V semiconductor tandem photoelectrodes. However, the expensive GaAs substrates and photocorrosion severely limited their ability to achieve the cost goal. We aim to tackle the challenges of achieving efficient, cost-effective PEC water splitting devices by developing tandem photoelectrodes, which consist of a bottom Si light absorber and a 1.7–2.0 eV top light absorber. High-performance top photoelectrode will be fabricated on large-area Si wafer using nanowire tunnel junction and will be passivated by an ultrathin N-rich GaN to protect against photocorrosion and oxidation.

The outcome of this project is to develop monolithically integrated Si-based tandem photoelectrodes, with the objective to achieve high efficiency (up to 20%) and long-term stability (>1,000 hours) in STH conversion through PEC water splitting. This project will be instrumental to establish an Si-based platform for high-efficiency PEC tandem water splitting devices and systems, which, to date, can only be achieved using prohibitively expensive GaAs-based materials. The stability of PEC water splitting devices will be fundamentally improved by utilizing N-terminated GaN protection layer. The semiconductor photoelectrodes are synthesized using industry-ready materials (e.g., Si and GaN based on standard semiconductor processing), and therefore the manufacture is controllable and scalable. The success of this project will help meet the DOE technical target for hydrogen production from PEC water splitting.

APPROACH

In this project, we aim to address the challenges of achieving efficient, cost-effective, PEC water splitting systems by combining the following unique approaches.

1. **We use Si as the bottom light absorber** to reduce the cost of the tandem water splitting devices, given its narrow energy bandgap and prevalence in industry.
2. **We use wide-bandgap GaN nanowire tunnel junction** to fabricate the top photoelectrodes on the Si platform. The GaN nanowire tunnel junction not only exhibits remarkably low resistivity but also further reduces the formation of defects and dislocations in the top light absorber because of the effective lateral surface stress relaxation.
3. **We use Ta_3N_5, BCTSSe, and $In_{0.5}Ga_{0.5}N$ semiconductors** as the top light absorber of the double-junction photoelectrodes. These materials have bandgaps in the range of 1.7–2.0 eV, can be controllably doped n or p-type and exhibit large light absorption coefficients and superior charge carrier transport properties. Recent studies have further shown that the conduction and valence band edge positions of Ta_3N_5 and $In_{0.5}Ga_{0.5}N$ straddle the water splitting potentials, promising photovoltages larger than 1.23 V.
4. **We use surface treatment and catalyst loading** to protect electrodes from corrosion and optimize water oxidation efficiency. We will incorporate a non-oxide coating (e.g., GaN) to eliminate this detrimental effect. We also have developed the chemistry and expertise at integrating a variety of water oxidation co-catalysts with photoanodes, which we have shown to improve the V_{on} by several hundred millivolts, which will be employed to optimize the performance of the proposed systems.

The research team consists of four investigators, including Profs. Z. Mi at University of Michigan, T. Hamann at Michigan State University, D. Wang at Boston College, and Y. Yan at University of Toledo. During the course of this project, we have established effective collaborations with the following nodes at the HydroGEN Energy Materials Network (EMN) to advance the proposed project.

1. "Surface Analysis Cluster Tool," Glenn Teeter, National Renewable Energy Laboratory (NREL). Surface characterization and in operando X-ray photoelectron spectroscopy (XPS) measurements are being performed on the various top photoelectrodes.

2. "Probing and Mitigating Chemical and Photochemical Corrosion of Electrochemical and Photoelectrochemical Assemblies," Francesca Toma, Lawrence Berkeley National Laboratory (LBNL). With the unique in situ techniques, including photoelectrochemical atomic force microscopy and scanning tunneling microscopy, Toma has provided services to understand the behaviors of our top electrode materials, and this information proves invaluable to our optimization efforts.
3. "Surface Modifications for Catalysis and Corrosion Mitigation," Todd Deutsch, NREL. This collaboration helps to identify the best strategy to protect the surface against photocorrosion and oxidation.
4. "Ab Initio Modeling of Electrochemical Interfaces," Tadashi Ogitsu, Lawrence Livermore National Laboratory (LLNL). This collaboration provides important insights of electrochemical interface and PEC device optimization through ab initio modeling and computational materials diagnostics.
5. "Computational Materials Diagnostics and Optimization of Photoelectrochemical Devices," Tadashi Ogitsu, LLNL. Dr. Ogitsu and his team members have performed first principles studies of N-terminated GaN surfaces and the effect on solar water splitting. These studies are further correlated with the stability analysis of the photoelectrodes.

RESULTS

Controlled Synthesis of Top Photoelectrode with E_g ~1.7–2.0 eV

Critical for achieving a high-efficiency double-junction photoelectrode is a top photoelectrode that has an energy bandgap ~1.7–2.0 eV, is stable in acidic solution, and can be controllably doped n- or p-type. In this project, we have demonstrated controlled synthesis of $In_{0.5}Ga_{0.5}N$, Ta_3N_5, and BCTSSe photoelectrodes, which have a direct bandgap of 1.7–2.0 eV. We have further demonstrated that the surface can be covered by an atomically thin N-rich protection layer, which can protect the top photoelectrode against photocorrosion and oxidation without compromising charge carrier extraction and STH conversion efficiency.

GaN and InGaN nanowires were grown on Si wafer using a molecular beam epitaxy (MBE) system equipped with a radio frequency plasma-assisted nitrogen source. The growth was conducted in N-rich conditions to promote the formation of N-terminated surfaces to protect against photocorrosion and oxidation. Photoluminescence (PL) spectra measured at room temperature for InGaN nanowires are shown in Figure 1. By changing the growth conditions, the PL emission wavelengths can be varied from ~500 nm to ~750 nm, corresponding to indium compositions of ~24% to ~51%, respectively. For indium compositions of 45%, the energy bandgap is ~1.8 eV, which can serve as the top electrode for an efficient double-junction photoelectrochemical device. Significantly, the band edges of such InGaN can straddle the water redox potentials, which is essentially required for unassisted solar water splitting. InGaN is doped p-type with Mg.

In parallel, extensive studies also have been performed on the synthesis of Ta_3N_5 and BCTSSe photoelectrodes. Ta_3N_5 was directly deposited on fluorine-doped tin oxide (FTO) substrates using a custom-built and fully automated atomic layer deposition system capable of operating at elevated temperatures with a maximum temperature of 640°C. For BCTSSe, we used mixed precursor films made by co-sputtering Cu, BaS, and SnS targets. The composition and thickness of the mixed precursor film were controlled by controlling the radio frequency powers and time applied to the targets. Detailed structural characterization has also been performed on these materials, which demonstrate a high level of crystallinity.

Critical for the operation of the monolithically integrated GaN/Si photocathode is the conduction band alignment between GaN and Si. To date, however, a direct measurement of the band alignment between Si and N-polar GaN was not available to our knowledge. Dr. G. Teeter's group at NREL performed XPS measurements on GaN/Si samples in a Physical Electronics 5600 instrument using monochromatic Al-kα illumination ($h\upsilon$ = 1486.6 eV) at a pass energy of 11.75 eV. Samples tested for XPS were bare n^+-Si(100), thin (~2–3 nm) n^+-GaN/Si(100), and relatively thick (~30 nm) n^+-GaN/Si(001). The samples were transferred under Ar and ultra-high vacuum into the XPS system. XPS survey spectra and high-resolution core-level spectra revealed acceptably low levels of surface contamination, enabling subsequent band-offset

measurements. A band diagram (Figure 1(b)) is constructed from the measured valence band maximums (VBMs) and the observed core-level shifts between these samples. The measured position of the VBM (1.16±0.05 eV) on the bare Si surface indicates that, within uncertainty, E_F is pinned above the CBM. Deposition of 2–3 nm of GaN evidently passivates the Si surface and induces a small amount of upward band bending. Assuming the GaN band gap = 3.39 eV, for this surface E_f is ~0.1 eV above the GaN CBM, indicating that this thin layer is degenerately doped *n*-type. The interfacial valence-band offset calculated from measured VBMs and core-level shifts was 2.44±0.1 eV. This value, in combination with the individual band gaps of Si and GaN, leads to a conduction band offset of -0.16±0.1 eV. Our measurements confirm for the first time that the CBM between N-polar GaN and Si is approximately aligned, thereby enabling efficient charge carrier (electron) transfer from Si to GaN.

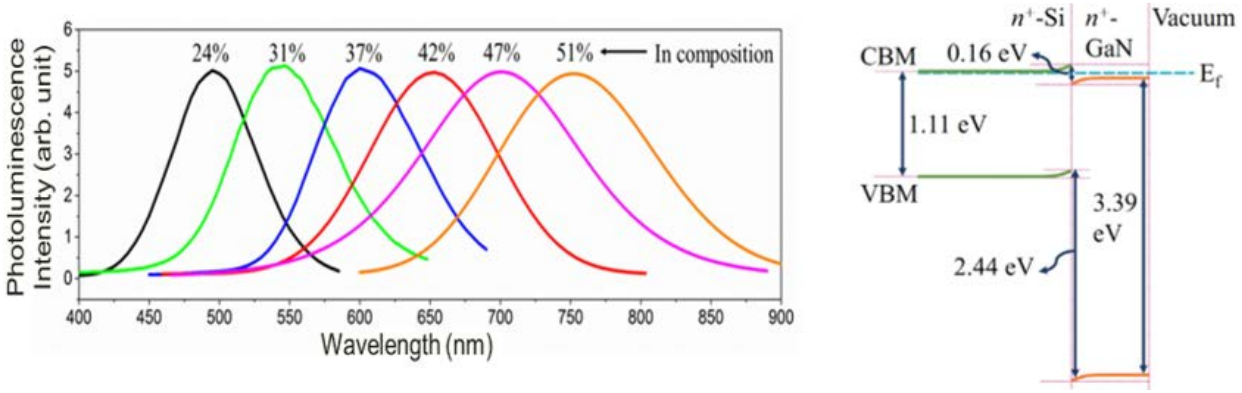

Figure 1. (a, left) Room-temperature photoluminescence spectra of different InGaN nanowires, showing that the photoluminescence emission peak can be controllably varied from 500 to 750 nm, corresponding to indium compositions of 24% to 51%. (b, right) Band diagram constructed for samples examined in XPS study for ~30 nm *n*+-GaN/*n*+-Si. The bulk E_f position in the *n*+-Si wafer is positioned just below the conduction band minimum (CBM), and the extents of band bending in each layer at the interface are assumed to be approximately equal.

Performance of Top Photoelectrode

Photoelectrochemical measurements of p-InGaN nanowire photocathodes were performed in 0.5 M H_2SO_4 solution (pH ~0) under the illumination of 100 mW/cm^2 simulated AM 1.5 G solar spectrum. Shown in Figure 2(a) is the linear sweep voltammetry measurement of p-$In_{0.42}Ga_{0.58}N$ tunnel junction photocathode. The onset potential is 0.79 V vs. NHE, and a relatively high photocurrent density of 12.3 mA cm^{-2} is measured at 0 V vs. NHE. The dark current density is negligible compared to the photocurrent, confirming the measured photocurrent comes from solar energy conversion. The improved onset potential and photocurrent density of p-InGaN tunnel junction nanowire photocathode is directly related to the efficient charge separation, hole collection, and electron extraction enabled by the integration with GaN tunnel junction. We have further performed continuous solar water splitting measurements on p-InGaN tunnel junction nanowire photocathode. Shown in Figure 2(b), the hydrogen evolution in 0.5 M H_2SO_4 solution was measured as a function of time at a constant photocurrent density of ~12 mA/cm^2 under AM 1.5 G one-sun illumination. The applied bias stays nearly constant at ~0 V vs. NHE, illustrated in Figure 2(b). It is seen that the measured and calculated hydrogen evolution agrees well, confirming a nearly unity faradaic efficiency.

Additionally, 230-nm-thick Ta_3N_5 films on FTO substrates and control FTO electrodes were coated with the CoPi water oxidation catalyst via electrodeposition in the light and dark, respectively, at a constant current of 10 μA/cm^2 for 8 minutes. The *J-E* curves of these electrodes under water oxidation condition at the neutral pH are shown in Figure 2(c). The shift in the potential required to sustain a given rate of water oxidation (i.e., current density) is a good measure of the photovoltage produced by the underlying semiconductor. From this plot, comparing the potentials needed to produce 1 mA/cm^2 indicates the Ta_3N_5 produces a photovoltage of

0.85 V, with a photocurrent onset potential of 0.5 V vs. RHE. This exceeds the milestone of a 0.5 V photovoltage.

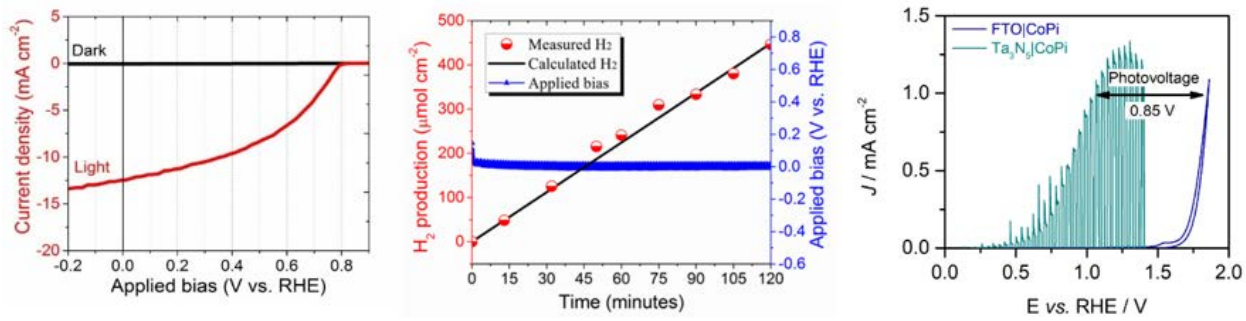

Figure 2. (a, left) Linear sweep voltammetry measurements of *p*-InGaN tunnel junction nanowire (*p*-InGaN/TJ/Si) in H_2SO_4 electrolyte (0.5 M, pH ~0) under simulated AM 1.5 G solar illumination of 100 mW/cm². (b, center) Hydrogen gas evolution under a constant photocurrent density of 12 mA/cm². The calculated hydrogen production from photocurrent is also shown (solid black curve). (c, right) Plots of *J-E* curves of CoPi-coated Ta_3N_5 and CoPi-coated FTO electrodes in chopped-light (1 sun) and dark conditions, respectively, in contact with 0.1 M potassium phosphate buffer solution at pH=7.

The performance of GaN/Si and T_3N_5 photoelectrodes has also been studied by Dr. T. Deutsch at NREL and Dr. F. Toma at LBNL. When a bias light was used, the incident photon-to-electron conversion efficiency improved dramatically, suggesting the photoelectrodeposition procedure is introducing electron trap states at the surface. NREL used atomic layer deposition to apply Pt to the GaN nanowires, which showed improved onset potential, likely due to the reduced trap states. PEC testing, XPS, inductively coupled plasma mass spectrometry, and in situ atomic force microscopy studies were carried out to systematically investigate the corrosion mechanism of Ta_3N_5 thin films. The results showed that the PEC performance of Ta_3N_5 degraded very fast when a constant bias was applied. This degradation of Ta_3N_5 was attributed to the formation of a few-nanometers-thick oxide layer at the surface during the first few minutes of PEC testing. Further analysis, such as in situ transmission electron microscopy and XPS beamline, will be conducive to qualitatively and quantitatively characterize this oxide layer, and provide insight into the corrosion mechanism of Ta_3N_5.

We also have focused on optimizing catalyst deposition with a balance between performance and cost by developing a non-aqueous method for catalyst deposition to reduce complications caused by catalyst growth in aqueous systems. It was found that Pt can be deposited on the Si photocathodes coated with GaN nanowires (GaN/Si) when the PEC water reduction occurred on the photocathodes at the same time, using a Pt mesh as the counter electrode in a one-chamber cell with a three-electrode configuration. Hydrogen evolution reaction performance of GaN/Si photocathode is improved by optimizing the non-aqueous PEC Pt deposition.

Performance of Si-Based Double-Junction Photoelectrode

Illustrated in Figure 3(a), the double junction photocathode consists of a *p*-InGaN top light absorber (In composition ~ 30%) and a Si bottom junction. The InGaN and Si segments are connected by an InGaN tunnel junction. Photogenerated electrons in the Si bottom light absorber recombine with photogenerated holes of the *p*-InGaN top light absorber. The PEC reaction was conducted in 0.5 M H_2SO_4 solution with Pt co-catalyst, silver chloride electrode (Ag/AgCl), and Pt wire as the working, reference, and counter electrode, respectively. A solar simulator (Newport Oriel) with an AM 1.5 G filter was used as the light source, and the light intensity was calibrated to be 100 mW/cm^2 for all experiments. Figure 3(b) shows the linear sweep voltammetry of platinized InGaN/TJ/Si double-junction photocathode (red curve) and platinized single-junction GaN/n^+-*p* Si photocathode (GaN/Si) (blue curve) under AM 1.5 G one-sun illumination and dark condition (black curve). The GaN/Si photocathode has V_{on} of ~0.5 V vs. RHE whereas the double-junction InGaN/TJ/Si has V_{on} of ~2.3 V vs. RHE, representing an enhancement of the photovoltage by ~1.8 V compared to the Si photocathode.

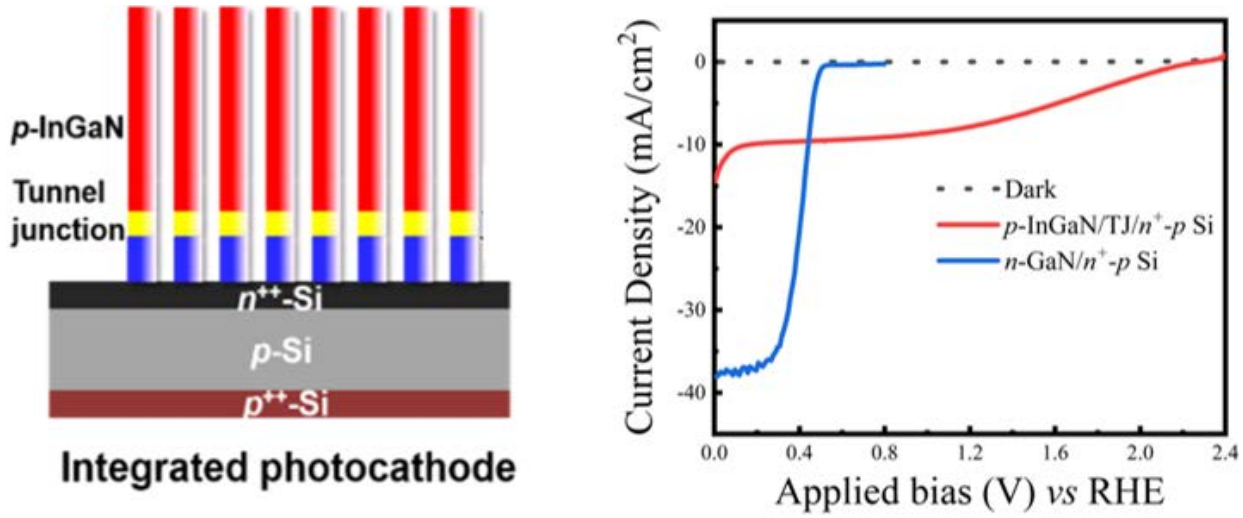

Figure 3. (a, left) Schematic illustration of a double-junction photocathode consisting of p-InGaN top junction and a Si bottom junction. The InGaN and Si are connected through a tunnel junction. (b, right) Linear sweep voltammetry measurements of the single-junction Si photocathode (blue curve) and InGaN/Si double-junction photocathode (red curve) in 0.5 M H_2SO_4 electrolyte under stimulated AM 1.5 G solar illumination of 100 mW/cm².

Long-Term Stability

We subsequently conducted a long-duration stability test for platinized n^+-GaN nanowire/n^+-p Si photocathode at 0 V vs. RHE in 0.5 M H_2SO_4 under AM 1.5 G one-sun illumination. Illustrated in Figure 4(a), the photocurrent density showed no degradation for a duration of 113 h. The observed fluctuation in current is due to the accumulation and release of hydrogen bubbles from the sample surface. To maintain the same experimental conditions, the electrolyte was changed after every 24 h. To our knowledge, this high stability measured at ~38 mA/cm^2 is the best for any semiconductor photocathodes tested at a photocurrent density of 30 mA/cm^2, or higher, when compared with 10 h for Pt (2 nm)/SiHJ [1], 24 h for Pt/TiO_2/F:SnO_2/Ti/n^+-p Si [2], and 4 h for Ru/TiO_2/p-InP [3]. We conducted detailed structural characterization of these samples through stability tests using scanning electron microscopy and transmission electron microscopy. The nanowire dimensions remained virtually the same compared to those before the experiments, suggesting that the nanowires were not etched during the long-term stability experiments. It is noticed, however, that the surface coverage of Pt nanoparticles was significantly reduced compared to that prior to the experiments. The underlying mechanisms for the long-term stability of GaN/Si photocathode are further discussed. Compared to conventional III-V semiconductors, III-nitrides have strong ionic bonds, which leads to the bunching of surface states near the band edge, rather than the forbidden bandgaps [4–5]. Therefore, the surface states of III-nitrides do not serve as nonradiative recombination centers, which is instrumental for achieving long-term stability against corrosion. Moreover, the nanowires grown by MBE have nearly perfect single-crystal wurtzite structure and are free of dislocations. Recent theoretical and experimental studies of the actual atomic structure of GaN nanowires grown by MBE further revealed that they exhibited a unique N-termination, not only for the $(000\bar{1})$ top faces but also for their nonpolar side faces [6]. Such N-terminated surfaces can further protect against corrosion during harsh PEC reaction.

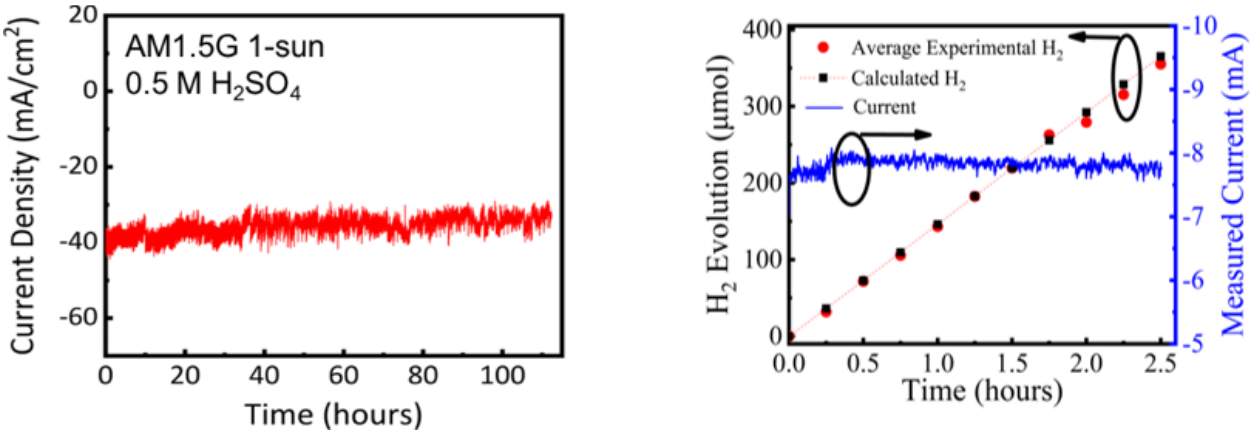

Figure 4. (a, left) PEC long-term stability measurement for platinized *n*$^+$-GaN nanowires/*n*$^+$-*p* Si photocathode at 0 V vs. RHE in 0.5 M H_2SO_4 under AM 1.5 G one-sun illumination. The photocurrent density of photocathode showed no degradation for >100 h duration (113 h). (b, right) Hydrogen generation for platinized *n*$^+$-GaN nanowires/*n*$^+$-*p* Si photocathode at 0.02 V vs. RHE under AM 1.5 G one-sun illumination in 0.5 M H_2SO_4 for 2.5 h. Blue curve represents the photocurrent, red dots represent the average amount of hydrogen generated at various times, and black dotted line is the theoretical amount of H_2 produced against time based on photocurrent. The Faraday efficiency is nearly 100%. The electrode area for the sample is 0.2 cm², which corresponds to a photocurrent density of ~ 39 mA/cm².

Investigation of Structural and Electronic Properties of Ga(In)N Surfaces

Dr. T. Ogitsu's group at LLNL has developed various structural models of GaN surfaces and GaN/water interfaces and has performed ab initio molecular dynamics simulations of these systems. It was found that N-rich and Ga-rich surfaces exhibited significant differences in the structural properties. The water molecules at the N-rich surface show a tendency of pointing their hydrogen atoms toward the surface N atoms, while the oxygen atoms are strongly attracted by the surface Ga atoms of the Ga-rich surface. In addition, the LLNL team has investigated the electronic structures of Ga(In)N alloys and the band bending of GaN for different surface terminations (Ga/N). Experimentally, it is known that In incorporation to GaN leads to significantly lower open circuit voltage (V_{OC}) than the theoretical value estimated from the bandgap, presumably due to imperfection in the system such as development of detrimental defects near the interface. These studies are to establish the reference points for further theoretical works with more realistic models (liquid-solid interface, incorporation of defects) as well as experimental calibration of our simulation.

CONCLUSIONS AND UPCOMING ACTIVITIES

In conclusion, this project is focused on the development of Si-based high-efficiency PEC tandem water splitting devices, with major innovations including the use of nanowire tunnel junction to fabricate 1.7–2.0 eV top photoelectrodes on Si wafers, and the discovery of N-terminated GaN to protect against photocorrosion. In this project, we have demonstrated 1.7–2.0 eV top photoelectrodes with improved performance. We have achieved photocurrent >12 mA/cm^2 at 0 V vs. NHE under one-sun illumination. We have further demonstrated InGaN/Si double-junction photoelectrodes. The photovoltage is enhanced by ~1.5 V compared to the Si photocathode. We have also demonstrated GaN/Si photocathodes with stable operation for >100 h at a very high photocurrent density of ~38 mA/cm^2 without using any extra surface protection. Detailed theoretical studies of the GaN surfaces and GaN/water interfaces have also been performed.

No additional work is currently funded, and there are no open issues remaining.

SPECIAL RECOGNITIONS AND AWARDS/PATENTS ISSUED

1. Zetian Mi was elected Fellow of Optical Society of America in 2018.

FY 2018 PUBLICATIONS/PRESENTATIONS

Journal Publications

1. F.A. Chowdhury, M.L. Trudeau, H. Guo and Z. Mi, "A Photochemical Diode Artificial Photosynthesis System for Unassisted High Efficiency Overall Pure Water Splitting," *Nature Communications* 9 (2018): 1707.
2. B. Zhou, X. Kong, S. Vanka, S. Chu, P. Ghamari, Y. Wang, N. Pant, I. Shih, H. Guo, and Z. Mi, "GaN nanowire as an outstanding linker of MoSx and planar silicon for photoelectrocatalytic water splitting," *Nature Communications* 9 (2018): 3856.
3. S. Vanka, E. Arca, S. Cheng, K. Sun, G.A. Botton, G. Teeter, and Z. Mi, "A High Efficiency Si Photocathode Protected by Multi-Functional GaN Nanostructures," *Nano Lett.* 18 (2018): 6530.
4. X. Guan, F.A. Chowdhury, Y. Wang, N. Pant, S. Vanka, M.L. Trudeau, L. Guo, L. Vayssieres, and Z. Mi, "Making of an industry-friendly artificial photosynthesis device," *ACS Energy Lett.* 3 (2018): 2230.
5. S. Chu, S. Vanka, Y. Wang, J. Gim, Y. Wang, Y.-H. Ra, R. Hovden, H. Guo, I. Shih, and Z. Mi, "Solar Water Oxidation by an InGaN Nanowire Photoanode with a Bandgap of 1.7 eV," *ACS Energy Lett.* 3 (2018): 307.
6. X. Guan, F.A. Chowdhury, N. Pant, L. Guo, L. Vayssieres, and Z. Mi, "Efficient Unassisted Overall Photocatalytic Seawater Splitting on GaN-Based Nanowire Arrays," *J. Phys. Chem. C.* 122 (2018): 13797.
7. Y. He and D. Wang, "Toward Practical Solar Hydrogen Production," *Chem.* 4 (2018): 405–408.

Conference Presentations

1. H. Hajibabaei and T. Hamann, "Direct Deposition of Crystalline Tantalum Nitride (Ta_3N_5) on FTO via High-Temperature Atomic Layer Deposition (ALD)," Gordon Research Conference; Renewable Energy: Solar Fuels, January 28–February 2, 2018
2. (Invited talk) D. Wang, "Understanding the Interface between Photoelectrodes and Catalysts," MRS Spring 2018, Phoenix, AZ, April 2–6, 2018.
3. (Invited talk) Yanfa Yan, "New materials for photoelectrochemical water splitting," 232nd Electrochemical Society Meeting, National Harbor, MD, October 2, 2017.
4. (Invited talk) Z. Mi, "Solar Water Splitting and CO_2 Reduction on III-Nitride Nanostructures," MRS Spring Meeting, Phoenix, AZ, April 2–6, 2018.
5. (Invited talk) Z. Mi, "Artificial Photosynthesis on III-Nitride Nanowire Arrays," 233rd Electrochemical Society (ECS) Meeting, Seattle, WA, May 13–17, 2018.
6. T.A. Pham, X. Zhang, B.C. Wood, S. Ptasinska, and T. Ogitsu, "Integrating Ab-Initio Simulations and Experimental Characterization Methods for Understanding Chemistry at Complex Photoelectrochemical Interfaces," MRS Spring 2018, Phoenix, AZ, April 2–6, 2018.
7. T.A. Pham, X. Zhang, B.C. Wood, S. Ptasinska, and T. Ogitsu, "Integrating Ab-Initio Simulations and Experimental Characterization Methods for Understanding Chemistry at Complex Photoelectrochemical Interfaces," ECS Meeting 2018, Seattle, WA, May 13–17, 2018.

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2. M.G. Kast, L.J. Enman, N.J. Gurnon, A. Nadarajah, and S.W. Boettcher, "Solution-deposited F:SnO(2)/TiO(2) as a base-stable protective layer and antireflective coating for microtextured buried-junction H(2)-evolving Si photocathodes." *ACS Appl Mater Interfaces* 6, no. 24 (2014): 22830–7.

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6. M.G. Kibria, R. Qiao, W. Yang, I. Boukahil, X. Kong, F.A. Chowdhury, M.L. Trudeau, W. Ji, H. Guo, F.J. Himpsel, L. Vayssieres, and Z. Mi, "Atomic-Scale Origin of Long-Term Stability and High Performance of p-GaN Nanowire Arrays for Photocatalytic Overall Pure Water Splitting." *Adv. Mater.* 28, no. 38 (2016): 8388–8397.