



Photoelectrochemical Hydrogen Production Using New Combinatorial Chemistry Derived Materials

**Thomas F. Jaramillo¹, Sung-Hyeon Baeck¹, Alan Kleiman-Shwarscstein¹,
Galen D. Stucky (PI)², Eric W. McFarland (PI)¹**

¹ Dept. of Chemical Engineering, ² Dept. of Chemistry & Biochemistry,
University of California, Santa Barbara
DOE Hydrogen Program DE-FC36-01GO11092

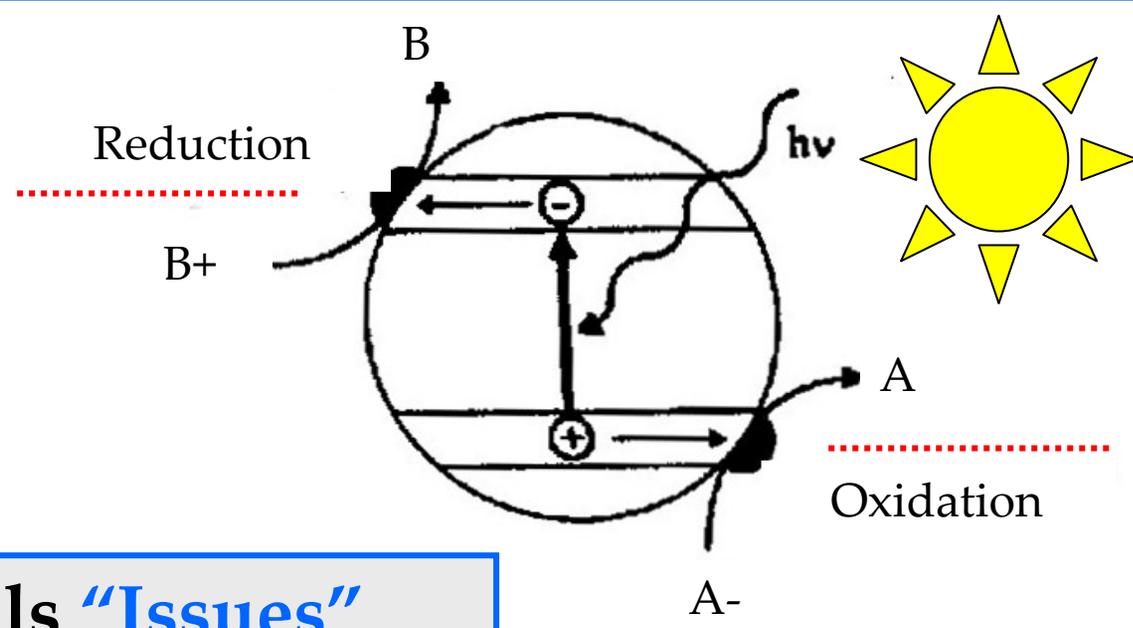
(September 2001 – August 2004)

Project ID#
PD22

This presentation does not contain any proprietary or confidential information.



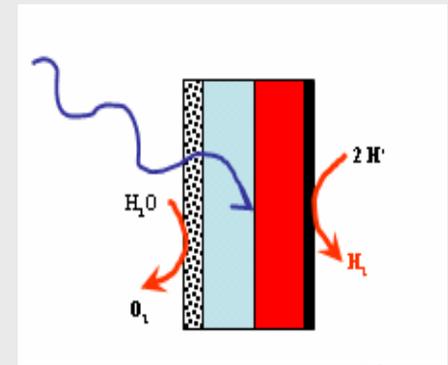
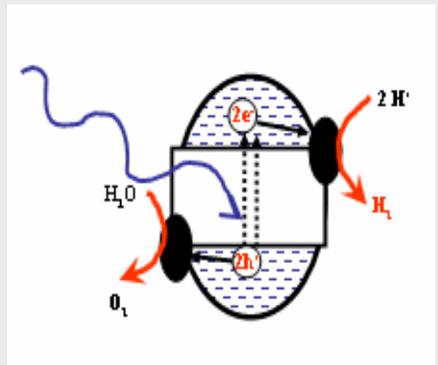
Photoelectrocatalysis



- Materials "Issues"**
- ❖ Absorbance
 - ❖ Charge Transport (e^-/h^+)
 - ❖ Surface States
 - ❖ Surface Electrocatalysis
 - ❖ Band Structure Energetics
 - ❖ **Stability and Cost**

Bulk Particulates

Structural Photoelectrodes



No presently known materials are suitable

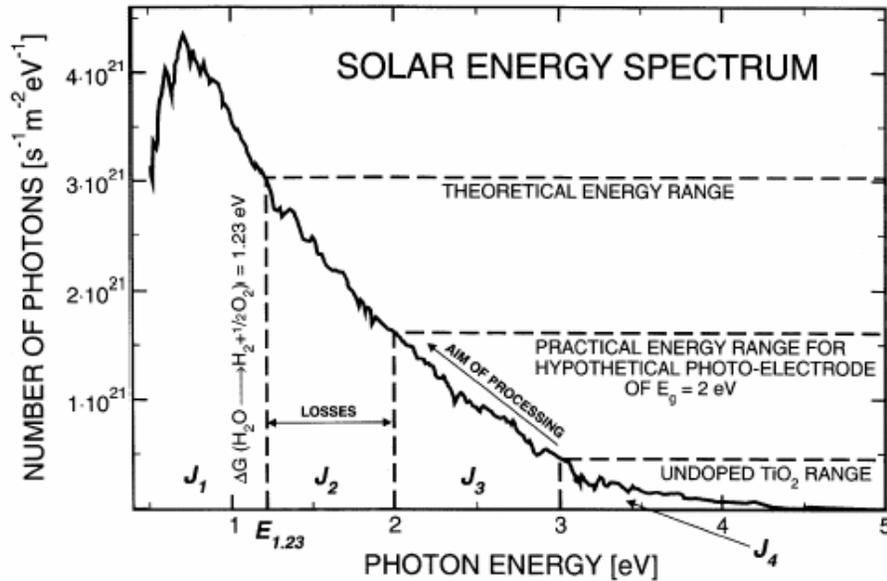


Photoelectrochemical H₂ Economics



~ 1000 W/m² available for harvesting.

“useful flux” ~ 10²¹ photons/m²-s day averaged @ > 1.5 eV



Solar Energy Spectrum (AM of 1.5) In Terms of Number of Photons vs Photon Energy

T. Bak, et al. *Int. J. Hydrogen Energy* 27 (2002) 991-1022.

Hydrogen for example

- ❖ @ 2e⁻ / H₂ -> 50e (kg H₂/m²-year)
- ❖ To compete with \$2-5/kg H₂ with an e ~10% system
- ❖ **ANY photocatalysis system cost (material+reactor) < \$20/m²-year**
- ❖ Compared to presently available 10Y-life Si solar panel ~ \$80/m²-year



Overview



Budget

- Project Funding From DOE for total 3 Year Program (\$624k)
 - Direct Costs \$446k
 - Overhead \$178k
- Year 3 Funding
 - Direct Costs \$152k
 - Overhead \$ 66k

Private and Public Interactions and Collaborations

- Upsala University, Sweden: collaboration on N-doped TiO₂ photocatalysts.
- Intematix Inc.: Characterization of PVD deposited film libraries, other planned collaboration outlined in newly submitted proposal.
- International Energy Agency: Participated in IEA Annex-14 Expert Group in the Hydrogen Implementing Agreement on photoelectrolytic hydrogen production.
- Mitsubishi Chemical: C60 activated metal oxide photocatalysts.
- General Electric: Seminar at CR+D, other planned collaboration outlined in newly submitted proposal.

Technical Barriers

This project addresses the following technical barriers from the Multi-Year Research, Development and Demonstration Plan Planned activities for 2003-2015 (Draft 6/3/03).

M. Material Durability

N. Material and System Engineering

O. Photoelectrochemical Efficiencies

DOE Technical Targets

Technical Targets	2003	2005	2010	2015
Solar-to-H ₂ Efficiency	7 %	7.5 %	9 %	14 %
Durability (hr)	100	1,000	10,000	20,000
Cost \$/Kg	N/A	360	22	5



Project Objectives: Year 3



- o Continue synthesis and screening of libraries designed in previous years and follow promising (lead) materials as they are identified.
- o Explore the composition-function relationship of dopants in ZnO hosts.
- o Investigate metal oxide libraries for electrocatalytic hydrogen production and expand our high-throughput screening to include electrocatalytic overpotential as a routine screen.
- o Develop a high-throughput optical screening system to measure the effective bandgap of metal oxides in libraries.
- o Synthesize and screen model libraries optically for bandgap as a primary screen; create secondary libraries of compositions with solar spectrum adsorption and subsequently screen the derivate libraries for appropriate redox/flatband levels and finally for H₂ production.
- o Continue to expand our investigations of nanoporous materials with the emphasis on ZnO, WO₃ and TiO₂.
- o Participate as a member of the USA Annex-14 Expert Group in the International Energy Agency's (IEA's) Hydrogen Implementing Agreement on photoelectrolytic hydrogen production.



Approach



(1) System Development

- ✓ Continuing synthesis & high throughput screening system upgrades
 - More samples / higher throughput
 - Faster measurements
 - Increased reproducibility
- ✓ Develop Automated Spray Pyrolysis Deposition System (ASPDS)
- ✓ Develop combinatorial slurry reactor for the production of hydrogen

(2) Library Synthesis and Screening

- ✓ Using new and existing high-throughput synthesis and screening technology, create and screen suitable new mixed metal oxide materials for electrochemical/photoelectrochemical hydrogen production.
- ✓ Improve and expand the chemical synthesis routes developed for automated high-throughput experimentation.
- ✓ Catalyze the surfaces and engineer the bandedges of the identified semiconductor materials as required.
- ✓ Synthesize, using conventional routes, selected materials identified in libraries for detailed structure-electronic analysis.
- ✓ Determine if existing photovoltaic (PV) device structures could be easily modified to effect the direct splitting of water.

Project Timeline

9/01 – 08/02

9/02 – 08/03

9/03 – 08/04

Phase I

Phase II

Phase III

NS IP C

I	System Development	<ol style="list-style-type: none"> 1. Development of Automated Electrochemical Synthesis Systems (Rapid Serial Electrochemical Deposition System (RSEDS) and Parallel Electrochemical Deposition System (PEDS)) 2. Development of High Throughput Photoelectrochemical Screening System (HTPESS) 3. Chemo-Optical High Throughput Hydrogen Screening System 		✓
	Library Synthesis & Characterization	<ol style="list-style-type: none"> 1. Tungsten oxide based libraries 2. Cu₂O based libraries 3. Cu₂O/TiO₂ heterojunction photoelectrode 		✓ ✓ ✓
II	System Development	<ol style="list-style-type: none"> 1. Development of Automated Spray Pyrolysis Deposition System (ASPDS) 		✓
	Library Synthesis & Characterization	<ol style="list-style-type: none"> 1. Combinatorial synthesis of mesostructured metal / metal oxide libraries (WO₃, ZnO, TiO₂, Pt) 2. Cobalt doped ZnO libraries for the improvement of visible light absorption 3. Electroless deposition of metal oxide libraries (WO₃, MoO₃) 		✓ ✓ ✓
III	System Development	<ol style="list-style-type: none"> 1. Development of Automated UV-VIS Spectroscopy 2. Development of slurry reactor for quantified hydrogen production from colloidal suspension powder photocatalyst 	✓	✓
	Library Synthesis & Characterization	<ol style="list-style-type: none"> 1. Continued synthesis & screening of ZnO based libraries 2. Fe₂O₃ based libraries by ASPDS 3. Tungsten-molybdenum mixed oxide libraries (W_xMo_{1-x}O₃) 4. Electrocatalytic nanoparticulate Au libraries 		✓ ✓ ✓ ✓

7

* NS: Not Started, IP : *In Progress*, C : Completed



Significant Achievements To Date



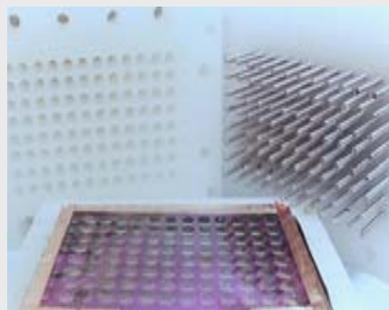
<p>1. Combinatorial System Development for Automated, High-speed Synthesis & Screening</p>	<ul style="list-style-type: none">✓ Parallel Electrochemical Deposition System (PEDS)✓ Rapid Serial Electrochemical Deposition System (RSEDS)✓ Automated Spray Pyrolysis Deposition System (ASPDS)✓ Photocurrent screening✓ Bandgap & bandedge measurement✓ Measurement of electrocatalytic properties
<p>2. Combinatorial Synthesis and Screening of Mixed Metal Oxides & Metal doped Oxides</p>	<ul style="list-style-type: none">✓ Tungsten-Molybdenum mixed metal oxides✓ Binary zinc oxides – significant (~ 4X) improvement of visible photocurrent in $Zn_{1-x}Co_xO$ materials ($0.03 < x < 0.05$)✓ Metal doped oxides (WO_3, TiO_2, ZnO, Cu_2O)
<p>3. Combinatorial Electrochemical Synthesis of Mesostructured Materials</p>	<ul style="list-style-type: none">✓ Mesostructured ZnO & WO_3 with Lamellar Phase✓ Mesostructured TiO_2 and Pt with Hexagonal Phase
<p>4. Combinatorial Synthesis of Nanoparticles by Pulsed Electrodeposition</p>	<ul style="list-style-type: none">✓ Fabrication of Nanoparticulate WO_3✓ Fabrication of nanoparticulate Pt/WO_3 for DMFC's✓ Fabrication of nanoparticulate Au, Pt
<p>5. Investigation of high activity for Au nanocluster electrocatalysts.</p>	<ul style="list-style-type: none">✓ Synthesis of nanoparticulate Au, Ir, and Pt by block copolymer micelle encapsulation✓ Electrocatalysis & gas phase catalysis



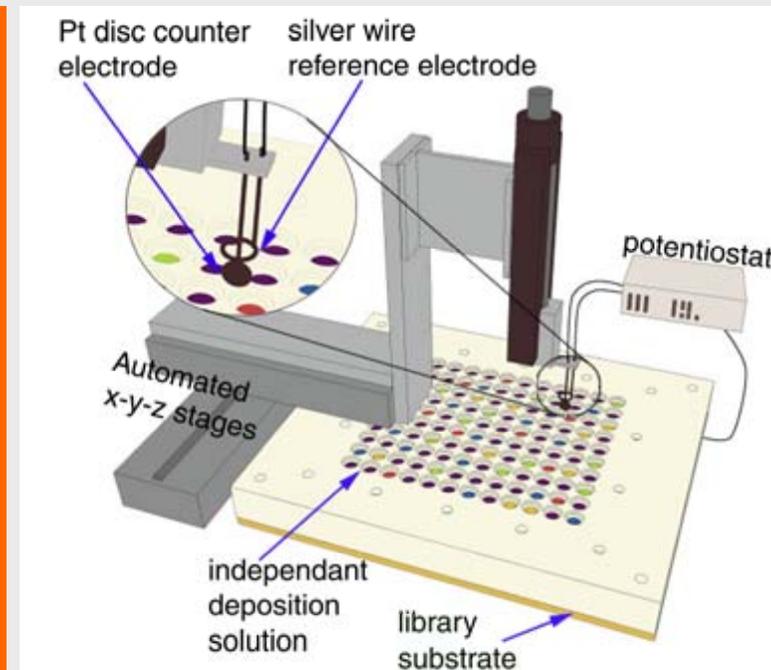
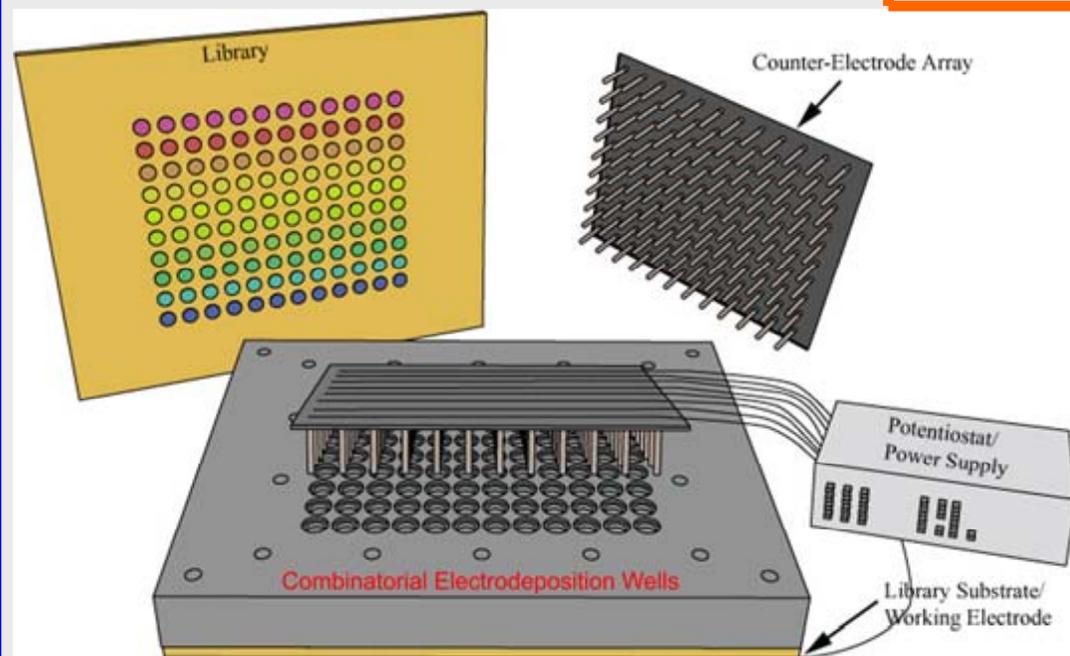
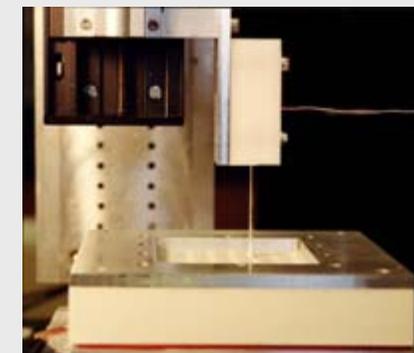
Automated (Combinatorial) Electrodeposition Systems



Parallel Electrochemical Deposition System (PEDS)



Rapid Serial Electrochemical Deposition System (RSEDS)



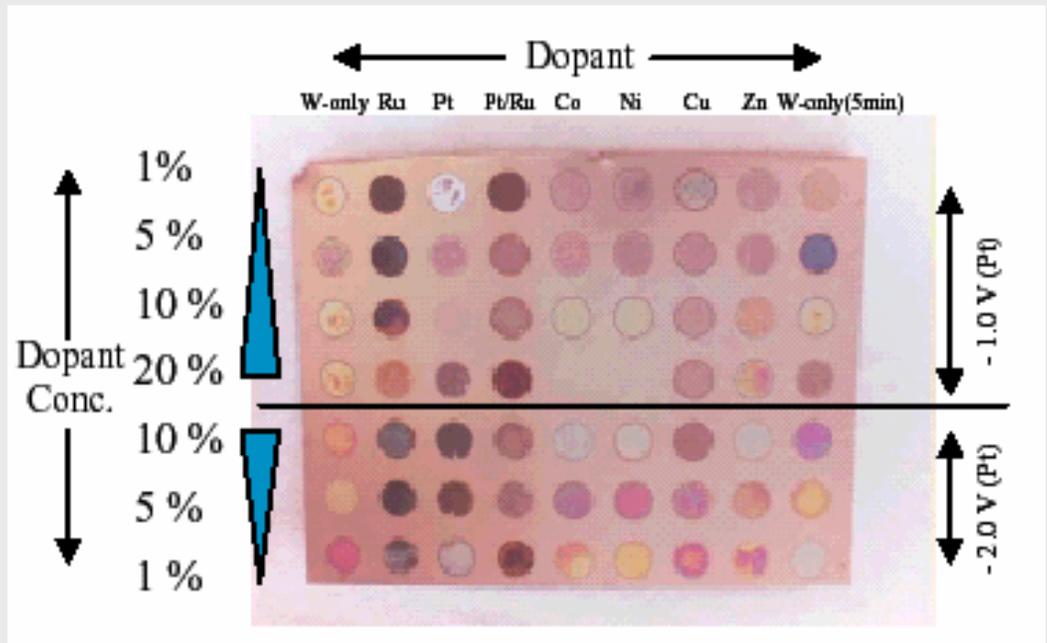


Photocatalyst Discovery is Well Suited to Combinatorial Chemistry



- ❑ Large interdependent parameter space to explore
- ❑ Limited theoretical understanding to predict optimal composition / structure
- ❑ Feasible to rapidly create and screen solid-state libraries
- ❑ Much to be learned about composition-structure-function relationships in photocatalytic materials
- ❑ **There has been no suitable material found to date**

Combinatorial Electrochemical Synthesis & Screening

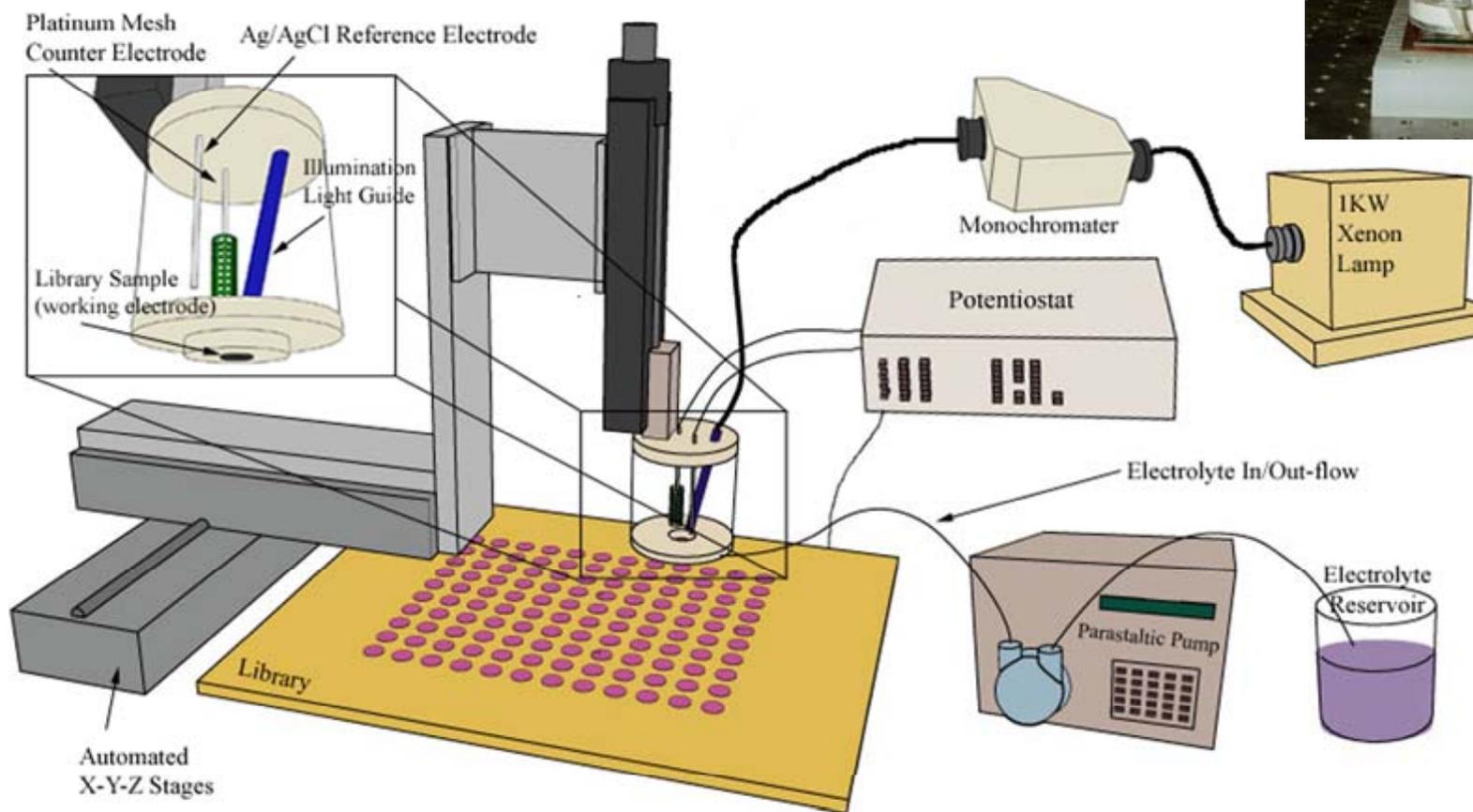
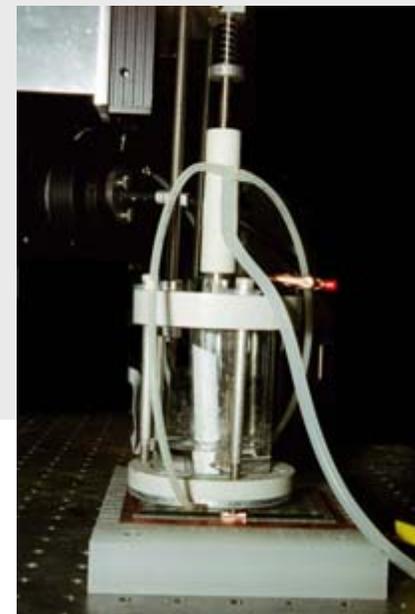


Diversity in...

Synthesis Parameters	Synthesized Materials
<ul style="list-style-type: none"> • solvent • electrolyte composition • ligands • surfactant additives • temperature • pH • voltage • current • time 	<ul style="list-style-type: none"> • composition • structure • thickness • crystallinity • surface states • morphology

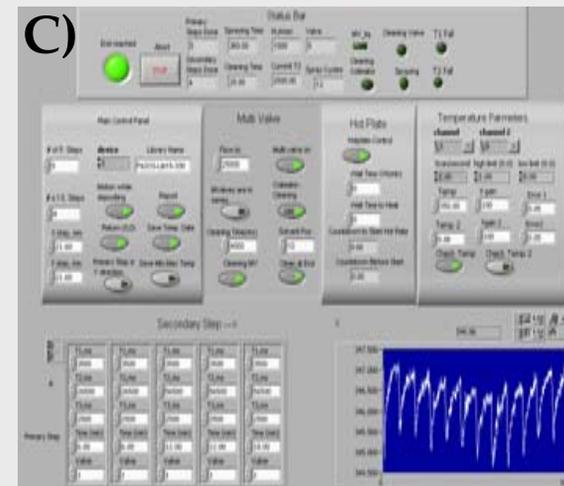
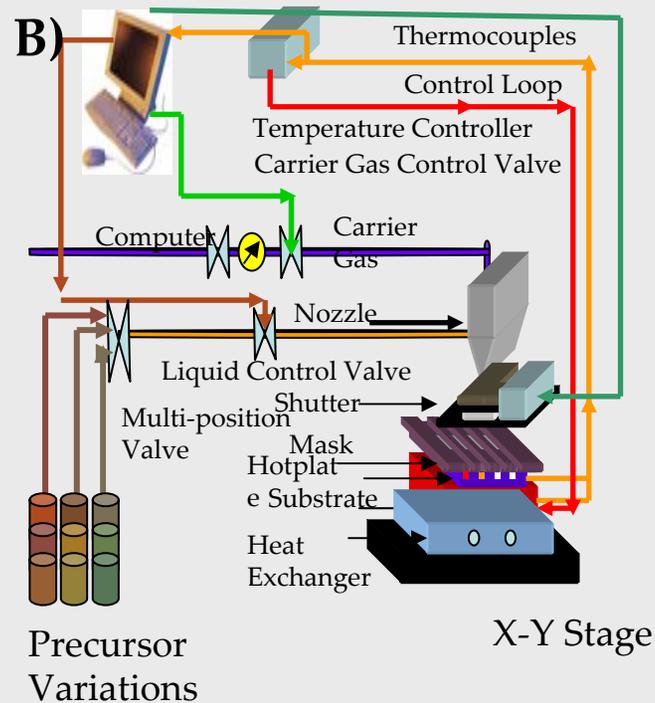
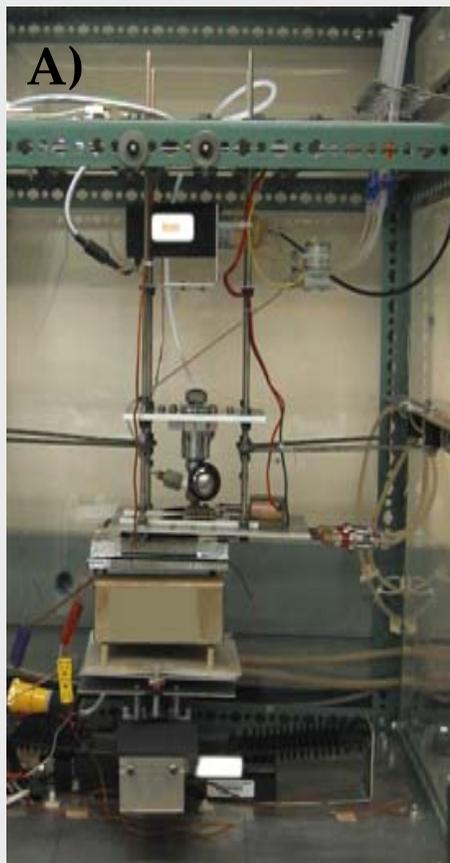
High-Throughput Photoelectrochemical Screening System (HTPESS)

The photoelectrochemical probe (magnified) is symmetrically stepped across the library surface to allow complete photoelectrochemical characterization of each material in the library under computer control.

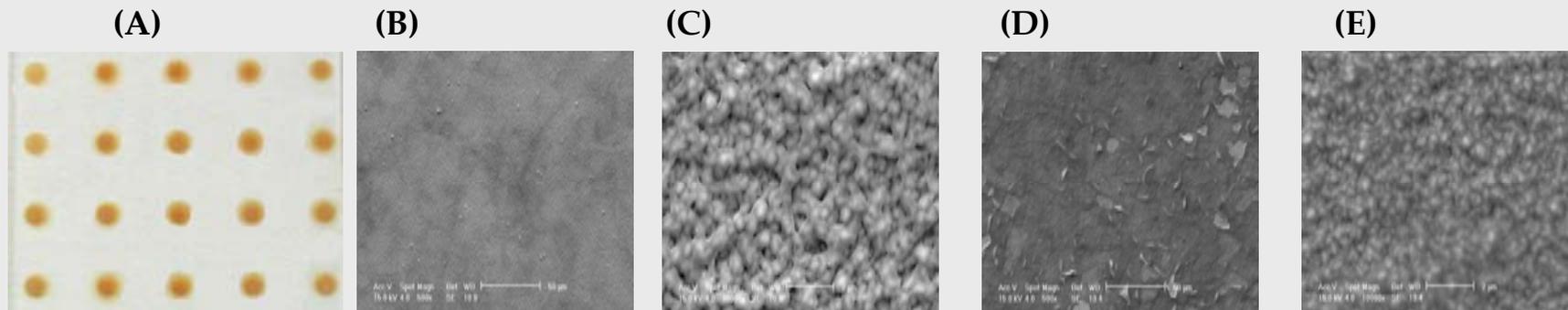




Automated Spray Pyrolysis Deposition System (ASPDS)

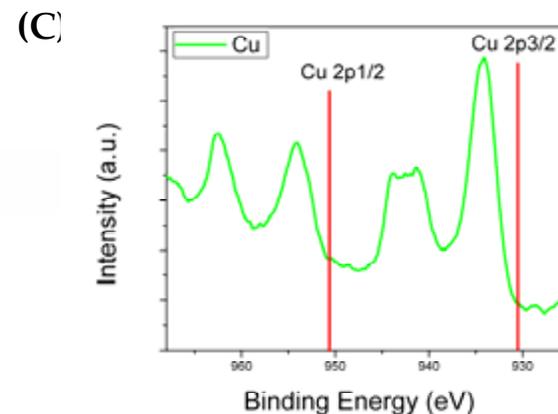
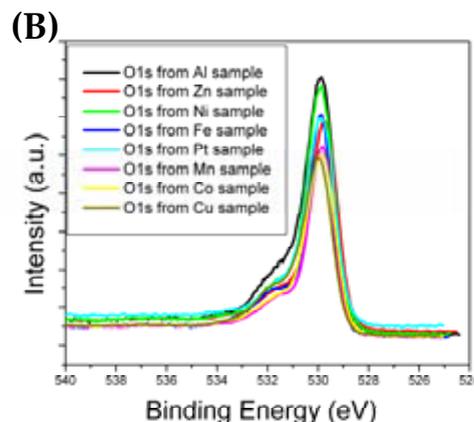
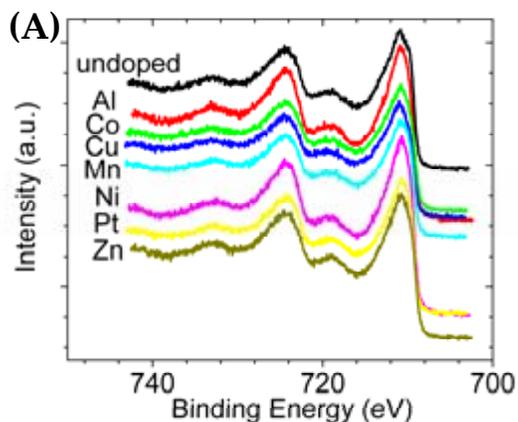


A) Photograph and B) Schematic diagram of ASPDS system; C) User interface



(A) Photograph of a 5x4 library (spacing = 0.125 in.) (B,C) SEM images of a film with 62.5% water (D,E) SEM images of a film with 52.5% water. Changes in morphology are observed as a function of water content in the electrolyte.

Film Characterization by XPS



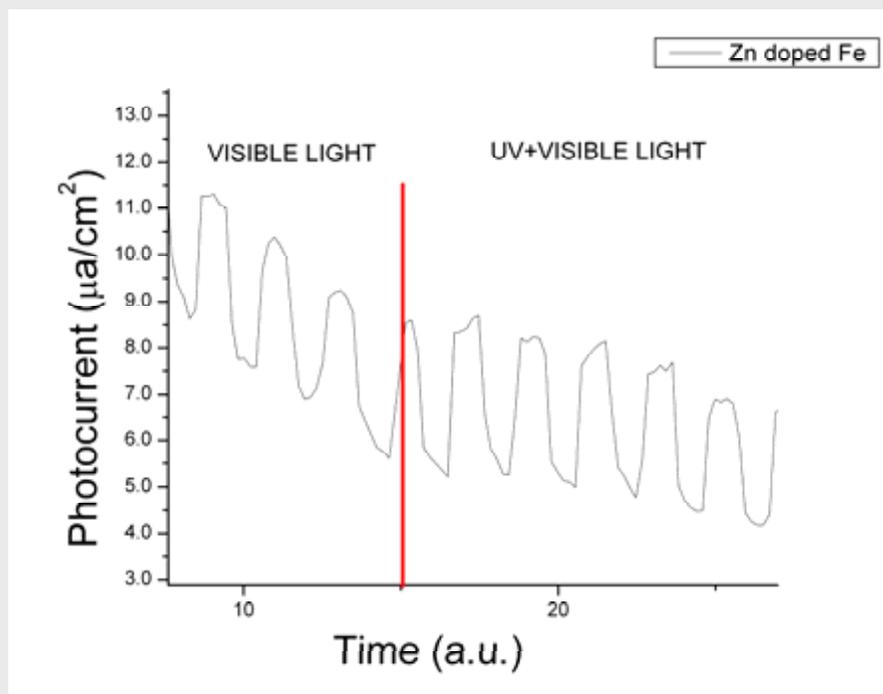
XPS data of iron oxide samples deposited by ASPDS (A) XPS data of Fe-2p on different doped iron oxide materials (B) XPS data of O-1s (C) XPS data of Cu-2p on the Cu-doped sample



Photoelectrochemical Screening of Fe_2O_3 materials synthesized by ASPDS



Zero bias photocurrent was measured under UV-vis and vis-only radiation.



Photocurrent from iron oxide doped with Zn (30%) deposited by spray pyrolysis ($\sim 1 \text{ W}/\text{cm}^2$ illumination)

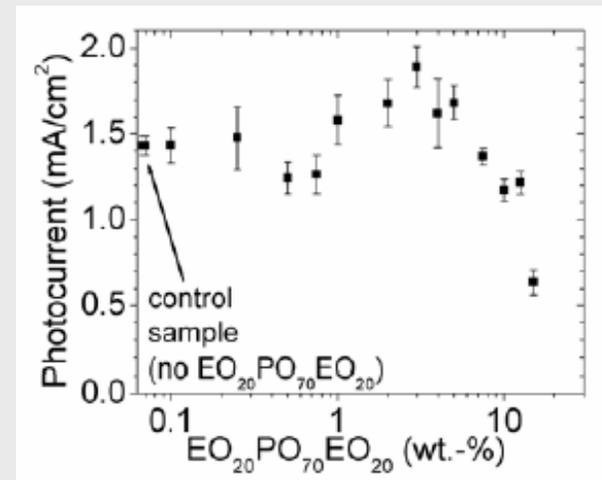
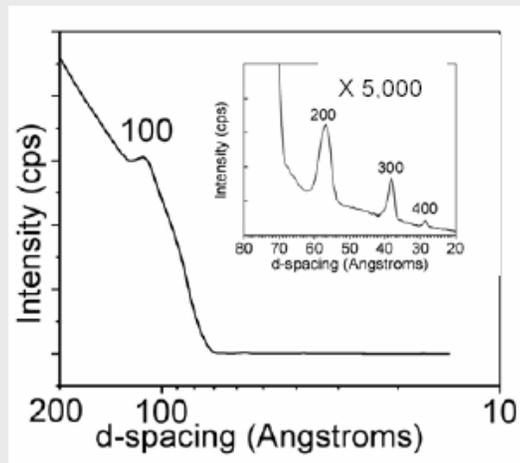
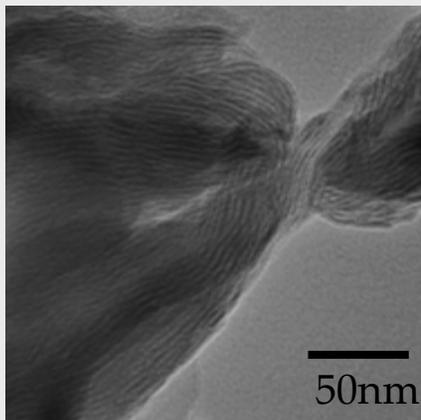
Preliminary Conclusions: The ASPDS can reliably and reproducibly synthesize samples; several steps are being taken to improve the crystallinity of iron oxides.



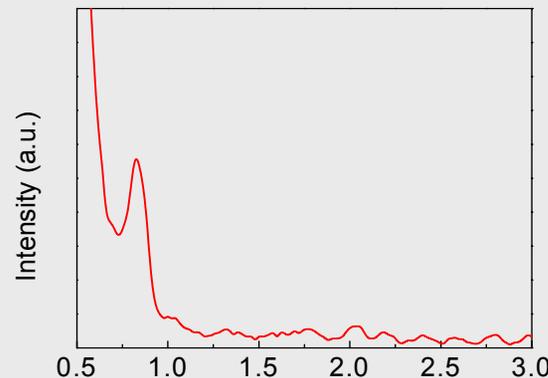
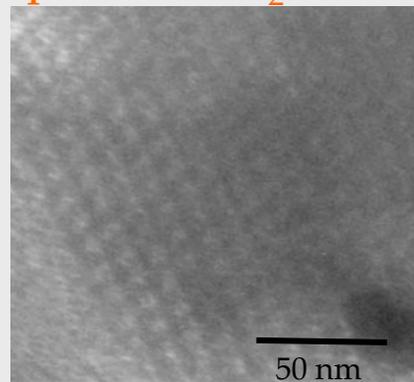
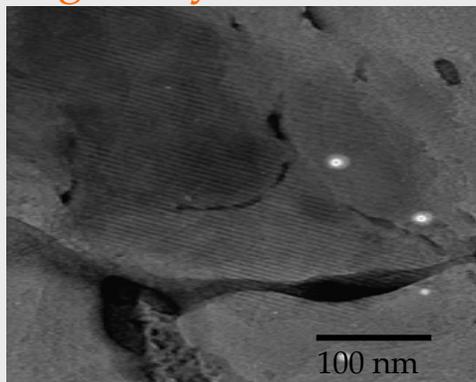
Electrochemical Synthesis of Mesostructured Materials



Lamellar ZnO



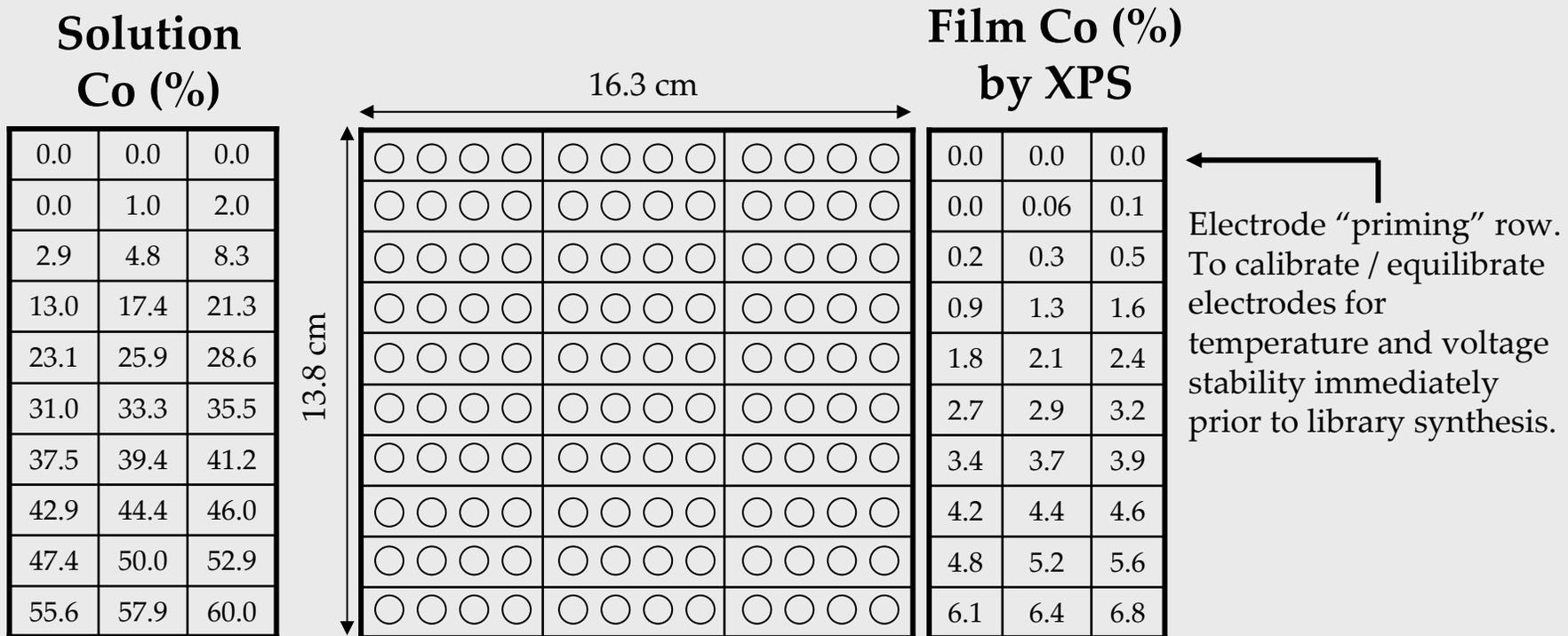
Hexagonally ordered Mesoporous TiO2



Mesostructured ZnO and TiO₂ were fabricated by surfactant-templated electrodeposition. (a) Lamellar-structured ZnO was observed by TEM, whose long range order was evidenced by XRD (b). (c) A library of mesostructured ZnO was photoelectrochemically screened and optimum concentration of the structure-directing agent (EO₂₀PO₇₀EO₂₀) was identified. Hexagonally ordered TiO₂ was also achieved (d,e,f).



Zn_{1-x}Co_xO Library Design



Rapid Serial Electrochemical Deposition System (RSEDS)

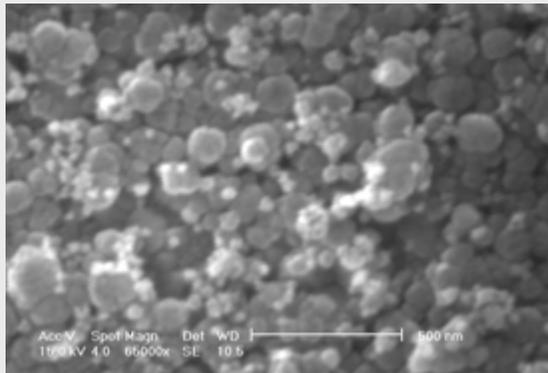
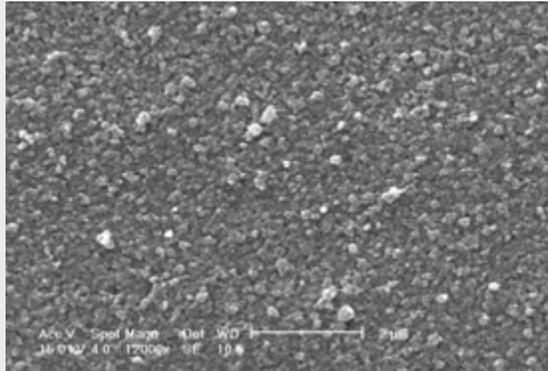
- 120 samples (10x12 array). 27 different Zn:Co ratios with 4 replicates each.
- 100mM ZnCl₂ & 60mM LiNO₃ in DMSO with varying concentrations of Co(NO₃)₂.
- 1.5mL of electrolyte solution. Sample size ~ 8mm diameter.
- Potentiostatic deposition @ -1.15V vs. Ag-wire (-1.0V vs. Ag/AgCl) reference
- Coiled Pt wire counter electrode
- Substrate: Pilkington TEC-15™ Fluorine-doped Tin Oxide (FTO) coated on glass
- 60 second deposition @ 105 °C (Total time for library synthesis: 4 hrs)
- Calcined 500 °C for 8 hrs.



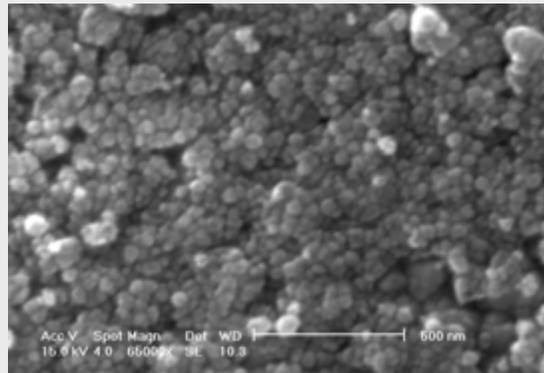
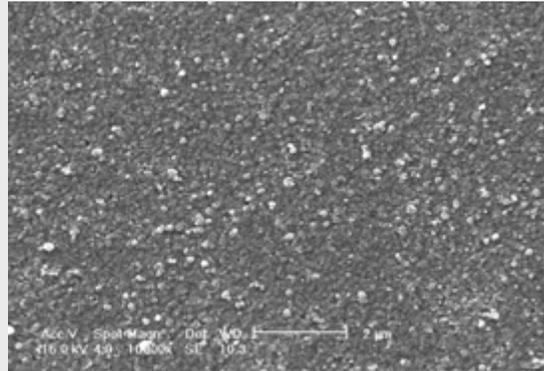
Zn_{1-x}Co_xO: Morphology by SEM



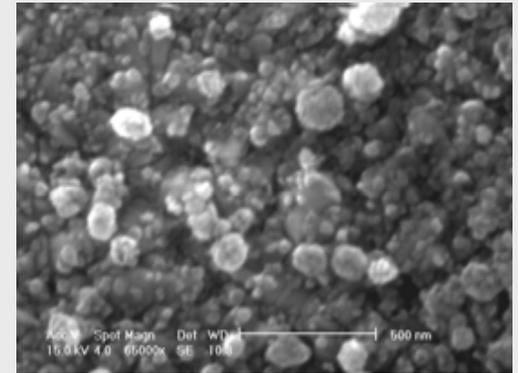
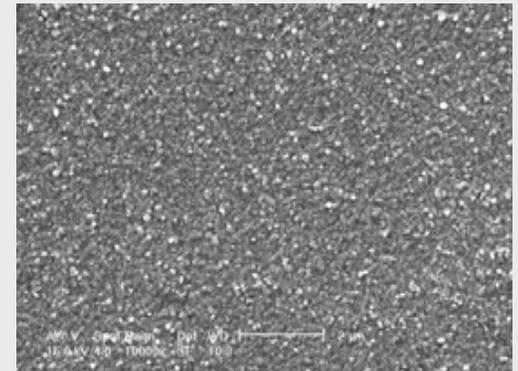
ZnO



Zn_{0.979}Co_{0.021}O



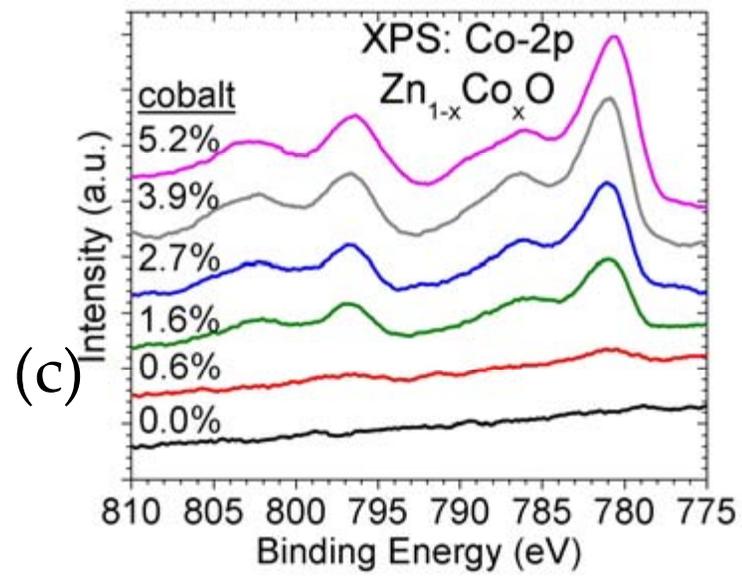
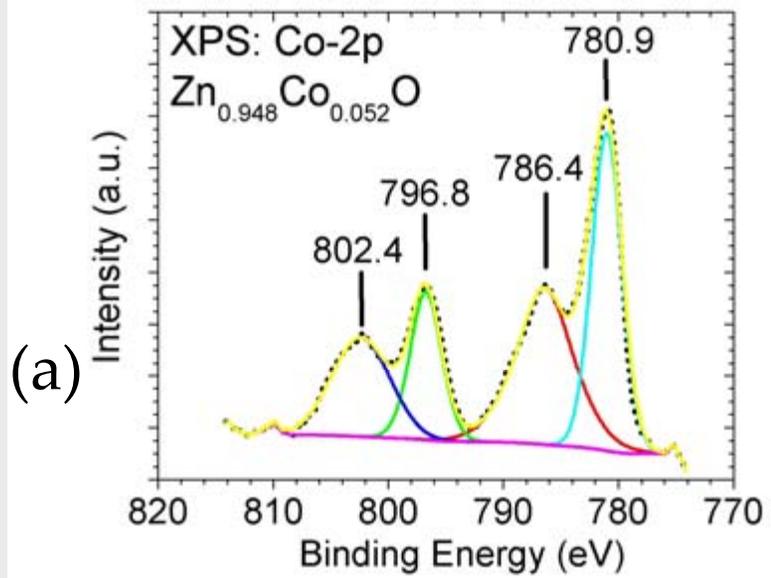
Zn_{0.948}Co_{0.052}O



SEM was conducted on 12 selected samples from the library. Film morphology for all samples, regardless of composition, resembled that of pure ZnO. Densely packed particles of 20-200 nm, shaped either as spheres or as platelets, were observed.



Zn_{1-x}Co_xO: Cobalt oxidation state by XPS



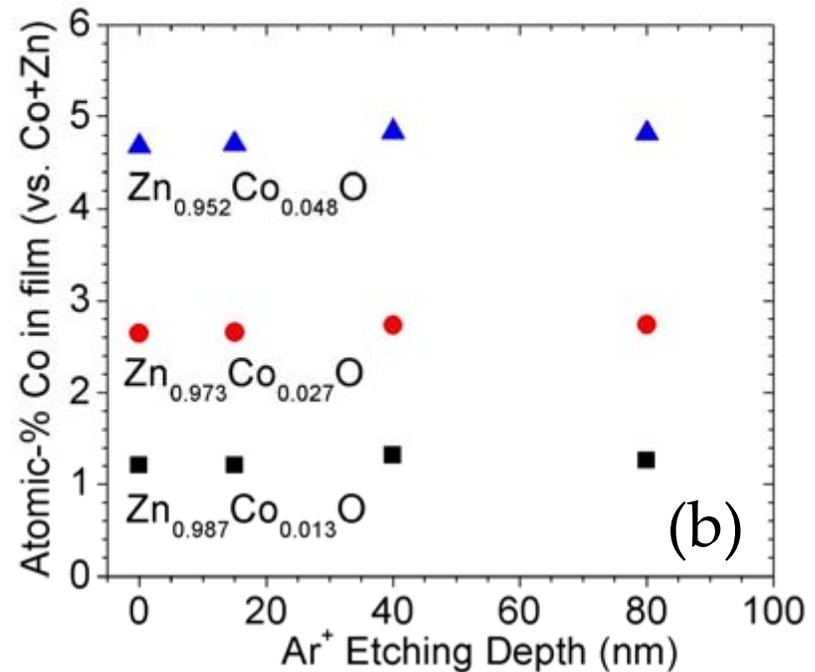
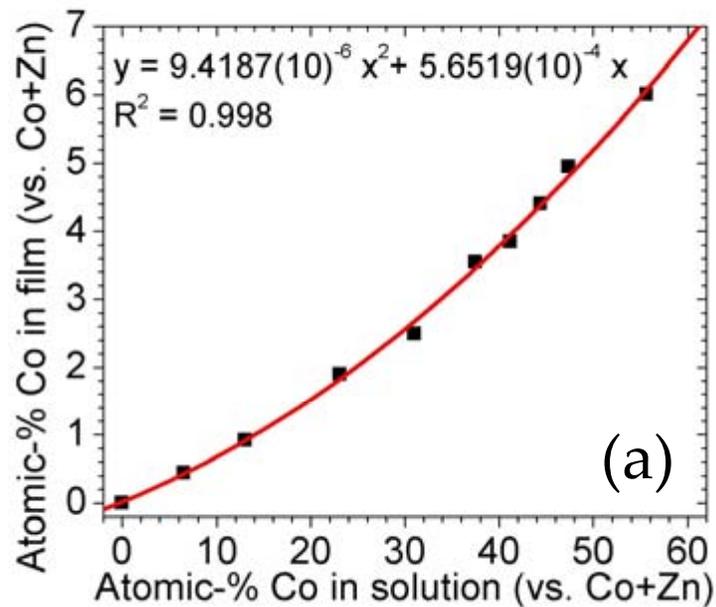
(b)

Spectral Region	Binding Energy & FWHM	Assignments
Co-2p _{3/2}	780.9 eV (3.1)	Co ²⁺ multiplet splitting
	786.4 eV (5.7)	Co ²⁺ shake-up satellite
Co-2p _{1/2}	796.8 eV (3.2)	Co ²⁺ multiplet splitting
	802.4 eV (5.9)	Co ²⁺ shake-up satellite

XPS was conducted on selected samples to determine Zn:Co stoichiometry as well as the oxidation state of cobalt. Graph (a) reveals the deconvoluted Co-2p spectrum of Zn_{0.948}Co_{0.052}O, in which all four cobalt peaks are assigned to Co²⁺, as indicated in Table (b). Graph (c) compares Co-2p spectra for several different compositions of Zn_{1-x}Co_xO, illustrating that Co²⁺ was the predominant species encountered for all samples.



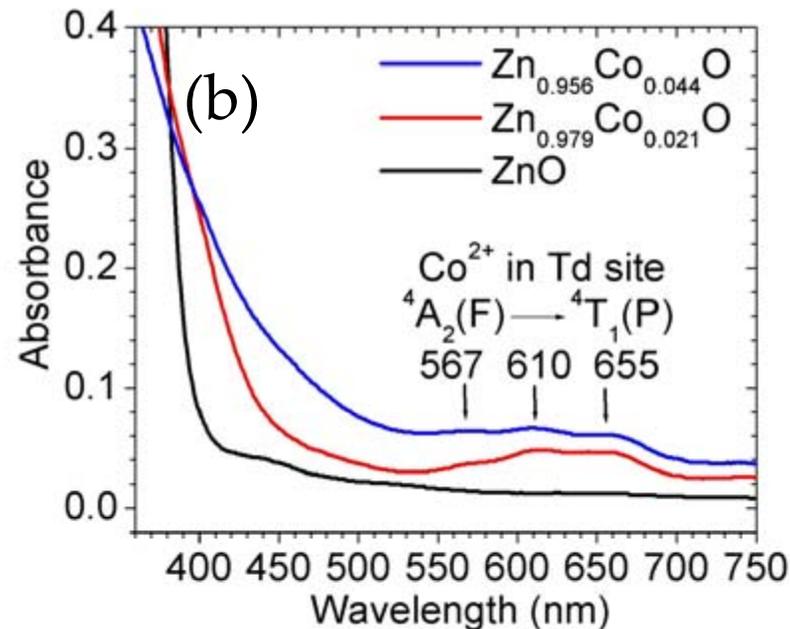
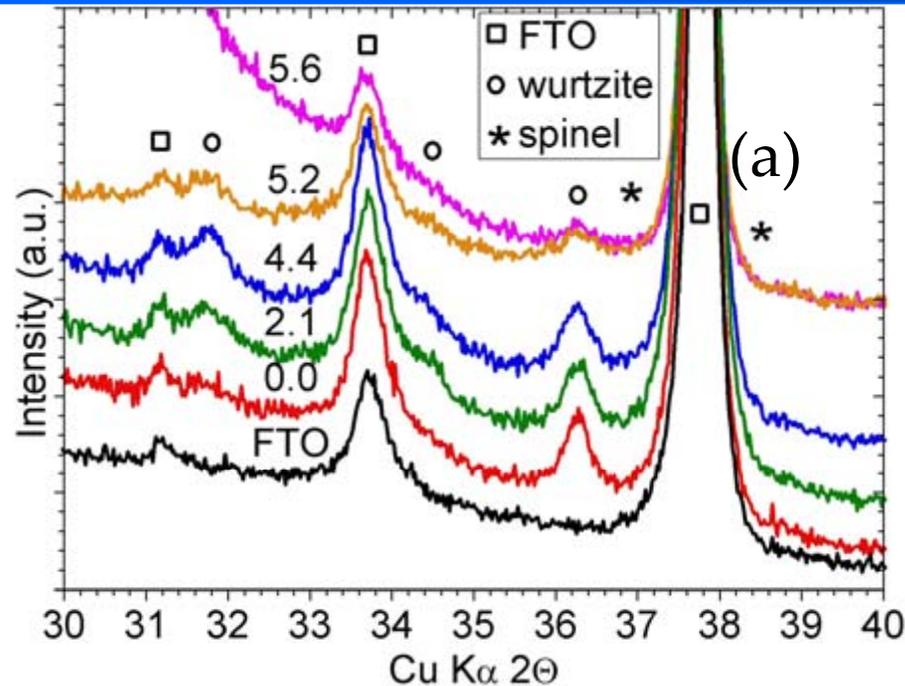
Zn_{1-x}Co_xO: Stoichiometry by XPS



Zn:Co stoichiometry was determined by the ratio of integrated peak areas assigned to Co-2p_{3/2} vs. Zn-2p_{3/2}, after normalizing areas with Scofield sensitivity factors. Graph (a) correlates Zn:Co stoichiometry in the films to Zn:Co ratios in the electrochemical deposition baths. A second-order polynomial was used to fit the data and a relationship was established ($R^2 = 0.998$). The fitted data was used to predict all film compositions within the library (see library design). Graph (b) shows film composition as a function of depth by Ar⁺ etching (4kV, 1.6mA, ~ 5nm/min). Although ion-etching is known to affect surface stoichiometry by selective etching, Zn:Co ratios in the film were found to be fairly consistent at all depths investigated. 19



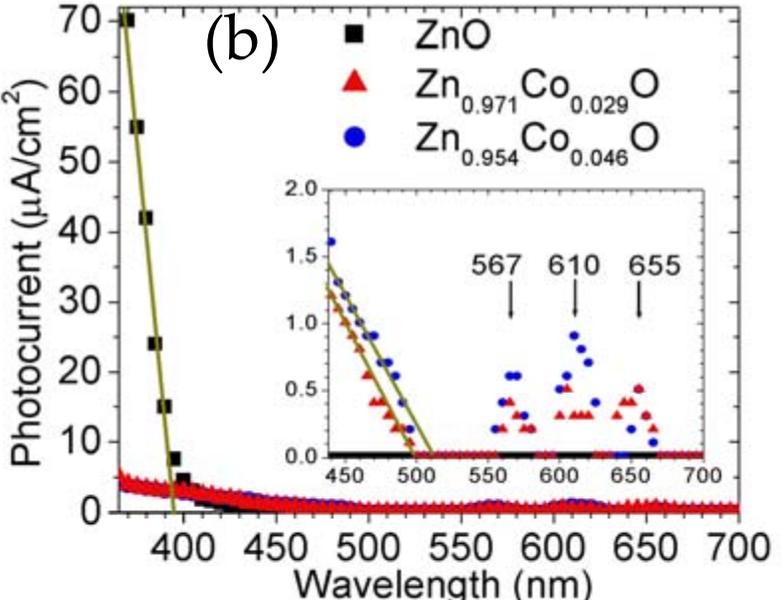
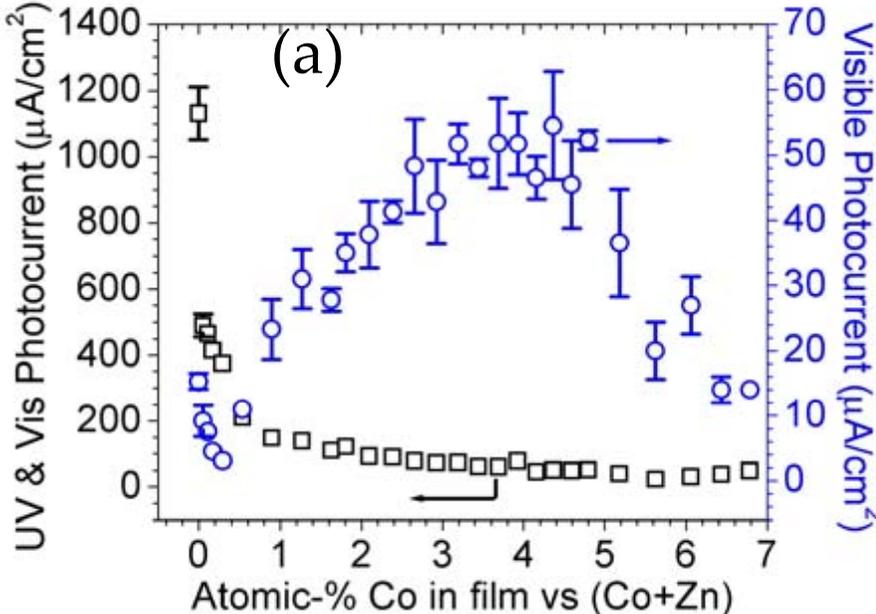
Zn_{1-x}Co_xO: Crystal structure (by XRD) & Optical absorption (by UV-Vis spec.)



(a) XRD was performed on selected samples for the purpose of identifying crystal structure of the mixed oxide. All compositions revealed a wurtzite structure typical of pure ZnO. No phase separation of CoO (rocksalt) nor spinel Co₃O₄ was observed, indicating that an atomically mixed Zn_{1-x}Co_xO (wurtzite) was synthesized for all values of x investigated. (b) UV-vis spectroscopy was conducted on several Zn_{1-x}Co_xO compositions, and even at low concentrations of Co, two trends emerge. First, the bandgap of Zn_{1-x}Co_xO decreases with increasing Co concentration, and secondly, peaks at 567nm, 610nm, 655nm are clearly present – characteristic *d-d* transitions of Co²⁺ within a tetrahedral site (consistent with the wurtzite structure). Increased visible absorption of ZnO by mixing with cobalt is promising for photoelectrochemical and photocatalytic applications.



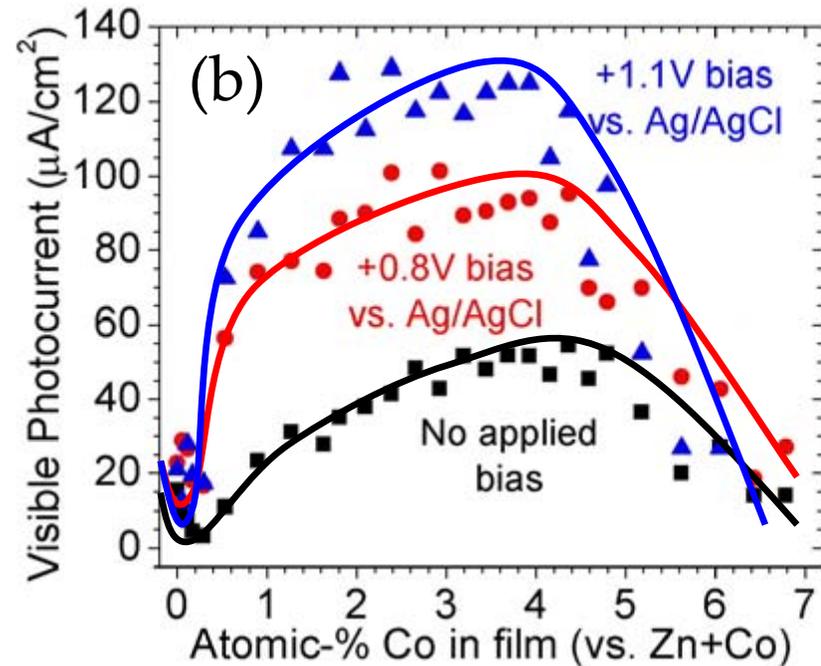
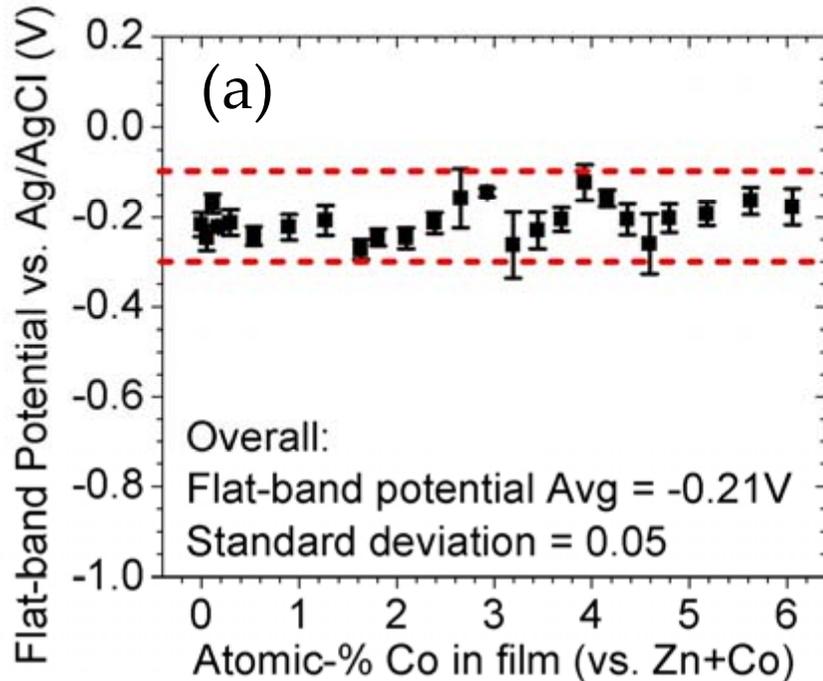
Zn_{1-x}Co_xO: High-throughput Photocurrent Screening



(a) The high throughput photoelectrochemical screening system was used to measure photocurrent (with no applied bias) under two conditions – first, with a UV-filter in the light path (“visible photocurrent”), and then without the filter in place (UV & Vis photocurrent). Under UV & Vis illumination, photocurrent drops sharply even with low concentrations of cobalt, and then decreases asymptotically (towards $\sim 60 \text{ mA}/\text{cm}^2$) with larger concentrations of cobalt in the film. Photocurrent under visible illumination reveals a very different trend. Initially, the visible photocurrent drops (with very low Co $< 0.5\%$), but the photocurrent increases steadily until a maximum is reached at 4.4% – 55 mA/cm^2 – nearly a four-fold improvement over pure ZnO (15 mA/cm^2). (b) Monochromated light was subsequently used for further high-throughput photoelectrochemical characterization. The action spectra of three selected samples are shown in Figure (b). Not surprisingly, the pure ZnO showed high photoactivity with illumination $< 400\text{nm}$, consistent with a ZnO bandgap of approx. 3.2eV. The inset shows a magnification of the 450nm – 700nm region, where clearly, the cobalt-doped samples exhibit strong photoactivity. Increased photocurrent in this region is derived from two sources – first, a decrease in the bandgap of these Zn_{1-x}Co_xO materials, and secondly from characteristic *d-d* transitions at 567nm, 610nm, and 655nm observed for tetrahedrally coordinated Co²⁺.



Zn_{1-x}Co_xO: Flat band potential & Photocurrent under applied bias



The high throughput screening system was used to take two cyclic voltammograms of each sample of the library under chopped illumination (first with and then without a UV-filter in place) in a 0.2M KNO₃ aq. electrolyte. This allows for measurement of flat-band potential (a) as well as photocurrent under applied bias (b). Clearly, flat-band potential changes negligibly as a function of composition, approximately $-0.21\text{V} \pm 0.05\text{V}$ vs. a Ag/AgCl reference electrode. This agrees with the notion that Co²⁺ substitutes Zn²⁺ in the ZnO lattice, as interstitial doping would have more likely increased the Fermi level of the material. Figure (b) shows, as expected, how photocurrent increases with increased applied bias. The shape of the curve is nearly identical in all three cases. Although a three-fold improvement is observed under a +1.1V applied bias (vs. Ag/AgCl), the energy input required does not justify its use for an industrial application. Nevertheless, the relatively small increase in photocurrent under such a large applied bias as compared to no applied bias indicates that charge separation is not a significant problem in either case.



Response to Previous Year Reviewer Comments



- Comment #1: Scale-up needs more emphasis
 - A scale-up photocatalytic reactor system has been developed using gas chromatography for quantitative measurement of H₂ & O₂ production on larger-scale samples (~ 1-20 grams).
 - Scale-up plans are greatly emphasized in the new proposal to DOE for FY 2005-2008 funding.
- Comment #2: Needs more focused direction
 - Response: Of the many mixed oxide systems we have investigated, we have focused on one promising host to pursue further studies and optimization. With Zn_{1-x}Co_xO (0.03 < x < 0.05) catalysts established as improved visible light photocatalysts.
 - Future work will focus on ternary and quaternary materials derived from this Zn:Co composition regime.



Future Work



- Perform exploratory design, synthesis and screening of new mixed metal-oxides based on solid solutions and substitutional doping of (at least) Zn, W, Fe, and Ti host oxides with the aim of improving the absorption of visible light to an equivalent of a material with a bandgap of approximately 1.7 eV.
- Continue to utilize our high-throughput screening systems to characterize photoelectrochemical performance and properties (including band edges) of library samples.
- Create four distinct forms of high surface area material systems. The morphologies will be either nanoparticulate or nanoporous and the composition will be either a single material or two materials:
 - homogeneous nanoparticles
 - heterogeneous nanoparticles
 - homogeneous nanoporous materials
 - heterogeneous nanoporous structures
 - We will quantitatively analyze the production of hydrogen and oxygen generated from these high surface area materials.
- Continue to investigate the synthesis of libraries of semiconductor heterostructures for improved efficiency and/or stability by creating libraries where heterojunctions will be formed both for passivating, otherwise unstable, material surfaces (e.g. wide gap oxide on narrow gap material) as well as for utilizing two-photon tandem absorption processes.
- Estimate hydrogen production costs using the best available laboratory energy efficiency data.



Publications resulting from DOE H₂ Program support (1 of 2)



Phase I (9/2001 ~ 8/2002)

1. C. Brandli, T.F. Jaramillo, A. Ivanovskaya, and E.W. McFarland, "Automated Synthesis and Characterization of Diverse Libraries of Macroporous Alumina," *Electrochimica Acta* **47** (4) 553-557 (2001).
2. T.F. Jaramillo, A. Ivanovskaya, and E.W. McFarland, "High-Throughput Screening System for Catalytic Hydrogen-Producing Materials," *J. Combinatorial Chem.* **4** (1) 17-22 (2002).
3. S.-H. Baeck, T.F. Jaramillo, C. Brandli, and E. McFarland, "Combinatorial Electrochemical Synthesis and Characterization of Tungsten-based Mixed Metal Oxides," *J. Combinatorial Chemistry* **4** (6), 563-568 (2002).
4. S.-H. Baeck and E.W. McFarland, "Combinatorial Electrochemical Synthesis and Characterization of Tungsten-Molybdenum Mixed Oxides," *Korean J. Chem. Eng.* **19** (4), 593-596 (2002).
5. S.-H. Baeck, T.F. Jaramillo, G.D. Stucky, and E. McFarland, "Controlled Electrodeposition of Nanoparticulate Tungsten Oxide," *Nano Letters* **2** (8) 831-834 (2002).
6. S.-H. Baeck, T.F. Jaramillo, and E.W. McFarland, "Influence of composition and morphology on photo and electrocatalytic activity of electrodeposited Pt/WO₃", *Am. Chem. Soc., Abs. Pap.* **224**: 062-FUEL Part 1 (2002).

Phase II (9/2002 ~ 8/2003)

7. K.-S. Choi, H. Lichtenegger, G.D. Stucky, and E.W. McFarland, "Electrochemical Synthesis of Nanostructured ZnO films Utilizing Self Assembly of Surfactant Molecules at Solid-Liquid Interfaces," *J. Am. Chem. Soc.* **124**(42) 12402-12403 (2002).
8. W. Siripala, A. Ivanovskaya, T.F. Jaramillo, S.-H. Baeck, and E.W. McFarland, "A Cu₂O/TiO₂ Heterojunction Thin Film Cathode for Photoelectrocatalysis," *Sol. Ener. Mat. & Sol. Cells.* **77**(3) 229-237 (2003).
9. K.-S. Choi, E.W. McFarland, and G.D. Stucky, "Electrocatalytic Properties of Thin Mesoporous Platinum Films Synthesized Utilizing Potential-Controlled Surfactant Assembly," *Adv. Materials.* **15** (23) 2018-2021 (2003).



Publications resulting from DOE H₂ Program support (2 of 2)



Phase II continued (9/2002 ~ 8/2003)

10. T.F. Jaramillo, S.-H. Baeck, B.R. Cuenya, and E.W. McFarland, "Catalytic Activity of Supported Au Nanoparticles Deposited from Block Copolymer Micelles," *J. Am. Chem. Soc.* **125(24)** 7148-7149 (2003).
11. B. Roldan Cuenya, S.-H. Baeck, T.F. Jaramillo, E.W. McFarland, "Size and Support Dependent Electronic and Catalytic Properties of Au⁰/Au³⁺ Nanoparticles Synthesized From Block Co-polymer Micelles," *J. Am. Chem. Soc.*, **125(42)**; 12928-12934 (2003).
12. S.-H. Baeck, T.F. Jaramillo, G.D. Stucky, and E.W. McFarland, "Synthesis of Tungsten Oxide on Copper Surfaces by Electroless Deposition," *Chem. Mater.* **15(18)** 3411-3413 (2003).
13. S.-H. Baeck, K.-S. Choi, T.F. Jaramillo, G.D. Stucky, and E.W. McFarland, "Enhancement of Photocatalytic and Electrochromic Properties of Electrochemically Fabricated Mesoporous WO₃ Thin Films," *Advanced Materials* **15(15)** 1269-1273 (2003).

Phase III (9/2003 ~ 8/2004)

14. T.F. Jaramillo, S.-H. Baeck, A. Kleiman-Shwarsstein, and E.W. McFarland, "Combinatorial Electrochemical Synthesis and Screening of Mesoporous ZnO for Photocatalysis," *Macromol. Rapid Commun*, **25**, 297-301 (2004).
15. S.-H. Baeck, T.F. Jaramillo, D.H. Jeong, E.W. McFarland, "Parallel synthesis and characterization of photoelectrochemically and electrochromically active tungsten molybdenum oxides", *Chem. Comm.*, **390-391** (2004).
16. J.M. Mwabora, T. Lindgren, E. Avendaño, T.F. Jaramillo, J. Lu, S.-E. Lindquist, C.-G. Grandqvist, "Structure, composition, and morphology of photoelectrochemically active TiO_{2-x}N_x thin films deposited by reactive DC magnetron sputtering" *J. Phys. Chem. B*, **108**, 20193-20198 (2004).
17. S.-H. Baeck, T.F. Jaramillo, A. Kleiman-Shwarsstein, and E.W. McFarland, "Automated Electrochemical Synthesis and Characterization of TiO₂ Supported Au Nanoparticle Electrocatalysts", *Meas. Sci. Tech.*, **16**, 54-59 (2005).
18. T.F. Jaramillo and E.W. McFarland, "Combinatorial investigation of Zn_{1-x}Co_xO for photoelectrochemical hydrogen production", *J. Comb. Chem.*, **7**, 264-271 (2005).



Hydrogen Safety



- The most significant hydrogen hazard associated with this project is: having a large (~ 300 cu. ft.) cylinder of compressed 99.999% hydrogen present in the laboratory.
- Our approach to deal with this hazard is: to have the cylinder securely fastened to the wall in a manner that was inspected and approved by UCSB Environmental Health and Safety.
- Other safety items to note
 - No accidents or injuries have been reported at anytime during the project (Sept 01- August 04).
 - All laboratory members are required to take a 4 hour course in laboratory safety, provided by UCSB EH&S.
 - UCSB EH&S routinely inspects the laboratory for safety to ensure compliance to federal, state, and county laws. Our laboratory has passed every inspection
 - As new equipment is installed and/or developed, the primary scientist responsible for that equipment is also responsible for:
 - Assessing safe operation protocol
 - Training other group members for safe operation of the equipment
 - No individual is permitted to operate equipment without consent of the primary scientist responsible for that equipment.
 - Hydrogen safety is inherent within this project because in combinatorial chemistry, only small amounts of each catalyst (\ll 1mg) are tested. Small amounts of catalyst yield low hydrogen/oxygen production rates well below flammable or explosive quantities in air or N_2 . 27