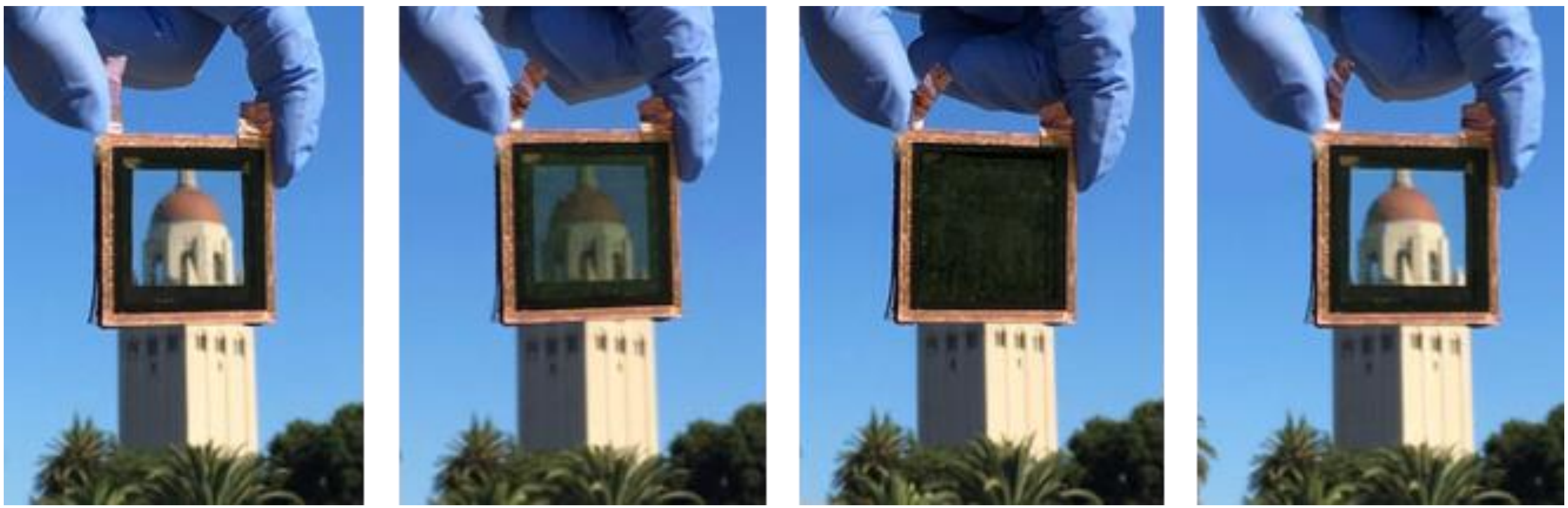
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Robust Large-Scale Dynamic Windows using Reversible Metal Electrodeposition



Stanford University, University of Colorado – Boulder
Professor Michael McGehee
michael.mcgehee@colorado.edu | (303) 492-2063

Project Summary

Timeline:

Start date: 10/31/17

Planned end date: 12/31/20

Key Milestones

1. Working electrode with <10% degradation over 2,000 cycles on 100 cm^2; BP1
2. 100 cm^2 device with <3 minute switching speed; BP1

Budget:

Total Project $ to Date:

- DOE: $55,104
- Cost Share: $28,922

Total Project $:

- DOE: $410,689
- Cost Share: $55,103

Project Outcome:

Our research group has successfully engineered dynamic windows based on reversible metal electrodeposition on a 100 cm^2 scale that switch uniformly and reversibly from transparent to opaque states. We have developed a durable counter electrode based on ion intercalation at lower cost than the transparent metal grid used in Gen 1 devices. We have successfully integrated this Li-intercalation based NiO counter electrode material into our dynamic windows. These windows can achieve color neutral opacity with fast switching speeds (<3 minutes) over 1000 cycles and also switch uniformly at a 100 cm^2 scale.

Team

Michael D. McGehee

- Principle Investigator
- Research Projects/Interests
  - Optically tunable dynamic windows based on reversible metal electrodeposition
  - Perovskite tandem solar cells
- *11th* most cited Materials Scientist in the world
- Former students have started more than a dozen companies

Tyler S. Hernandez

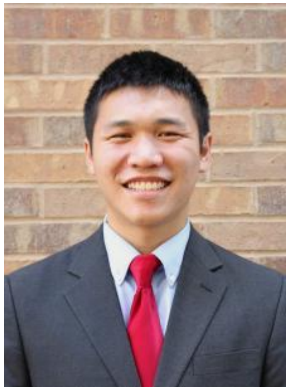
- 4th year Inorganic Chemistry Ph.D. Candidate
- Research Projects/Interests
  - Reversible, aqueous electrolytic systems
  - Low-cost, high throughput ion-intercalation based counter electrode materials
- NSF Fellowship

Michael T. Strand

- 3rd year Materials Science and Engineering Ph.D. Candidate
- Research Projects/Interests
  - Nanostructured, highly durable working electrode surfaces
  - Device modelling and electrode design
  - Scaling RME windows to commercial size
- NSF Fellowship, Stanford Graduate Fellowship

Andrew L. Yeang

- 2nd year Chemical Engineering Ph.D. Candidate
- Research Projects/Interests
  - Non-aqueous electrolyte compatible with reversible metal electrodeposition and ion intercalation
  - Polymer gel electrolyte with high stability and reversibility for RME dynamic window applications



Company Collaborative Interest:

Velux, Robert Clarke Associates, AGC, AGP, Pilkington, Cardinal, Glas Trosch, Corning, Tesla, Boeing, Nitto Denko, Avery Dennison, BASF, Solvay, View, Gentex, Wisp, and Kinestral

Challenge

There is burgeoning interest in commercializing dynamic windows that enable electronic control of visible light and solar energy. Two companies recently raised more than $1.5 billion in private investments based on the potential of dynamic windows to increase occupant comfort and energy efficiency. In buildings, dynamic windows result in an average of 10% energy savings over static low-E windows due to reduced lighting, heating, and cooling costs. In addition, dynamic windows look substantially better than windows with blinds and are far more likely to be adjusted optimally since they can be automated with a computer.

Over the past several decades, researchers have explored numerous dynamic window technologies. The majority of this research has focused on electrochromic materials which change color upon application of a voltage. It is difficult using these materials, however, to simultaneously exhibit the fast switching times, color-neutral tinting, long-term durability, and low cost needed to achieve widespread commercialization. We are developing dynamic windows based on reversible metal electrodeposition to address the market need for this technology.

There is a trade-off between energy efficiency and occupant comfort.

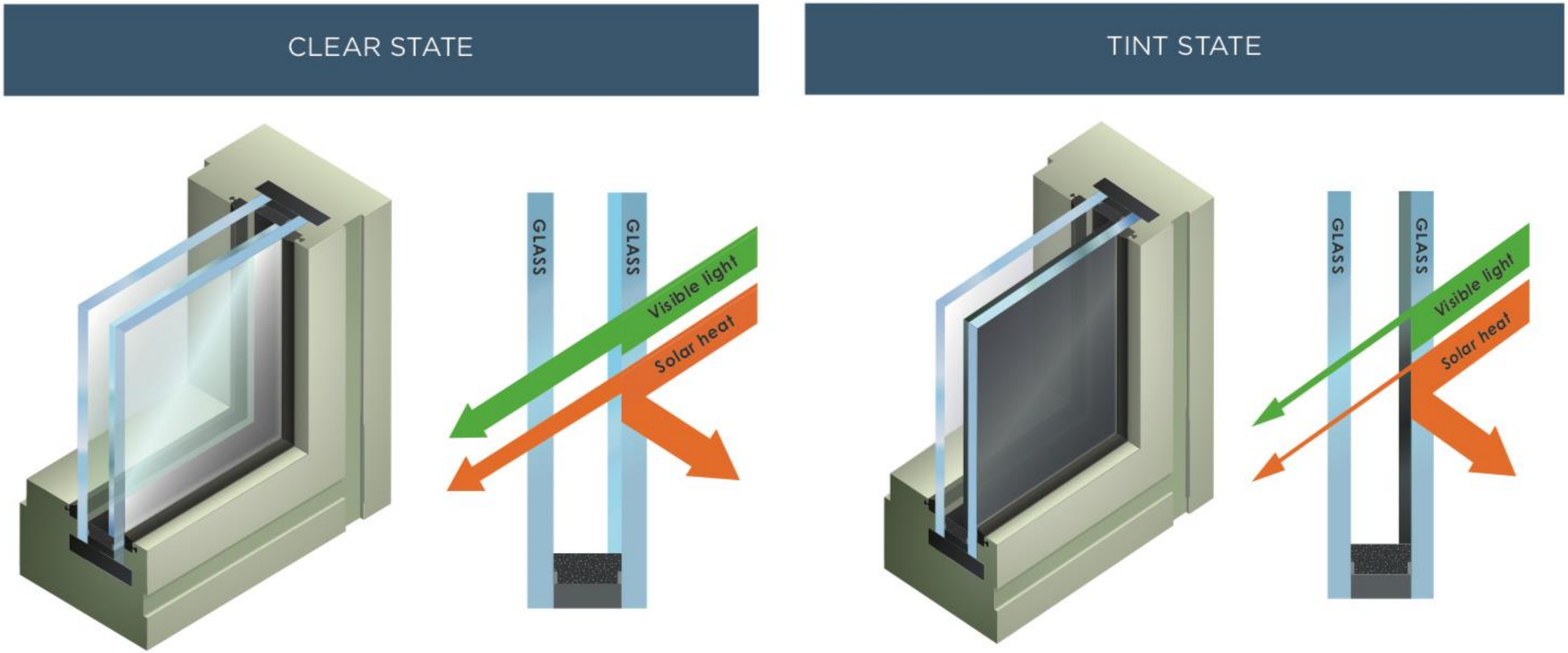
vs.

Energy Efficiency

Occupant Comfort

Source: https://en.wikipedia.org/wiki/Window_tax, http://www.archdaily.com/793971/roy-and-diana-vagelos-education-center-diller-scofidio-plus-renfro

Dynamic windows improve efficiency without sacrificing the view.



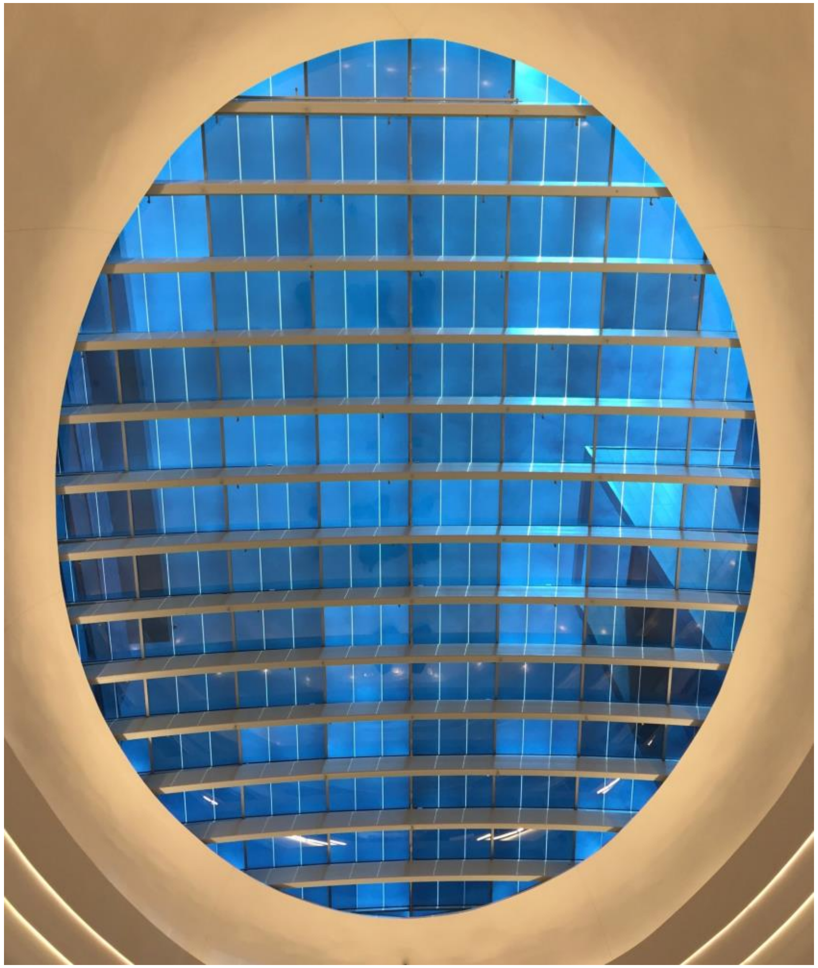
Up to 20% energy savings compared to static glass!

Source: https://view.com/assets/pdfs/igu-data-sheet-us.pdf,

Conventional technologies have drawbacks.

- Blue color
- Slow switching
- Limited contrast
- High cost

SageGlass view



Reversible Metal Electrodeposition (RME) for Dynamic Windows

Metals are great attenuators of light

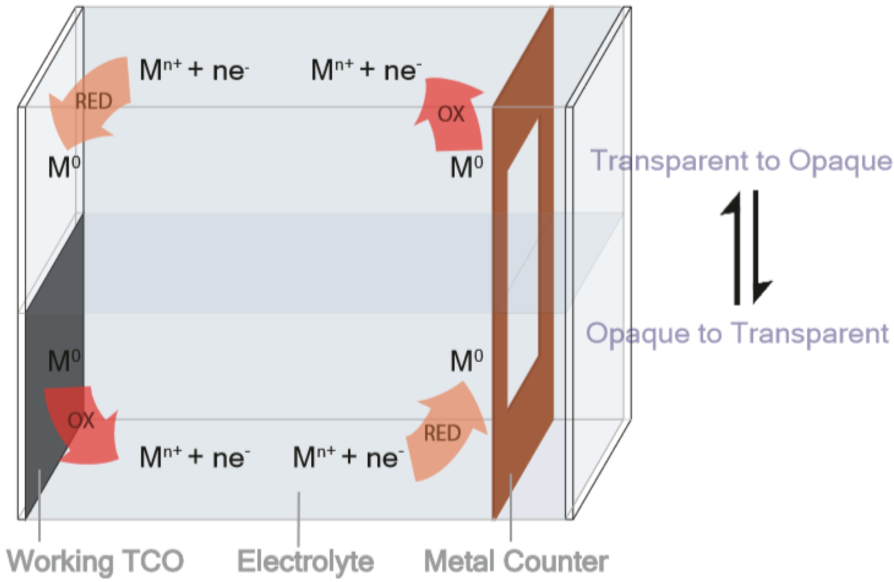
- Completely opaque at 20-30 nm thickness
- Reflective or absorptive (mirror or black)
- Can achieve <0.1% transmission (privacy applications)

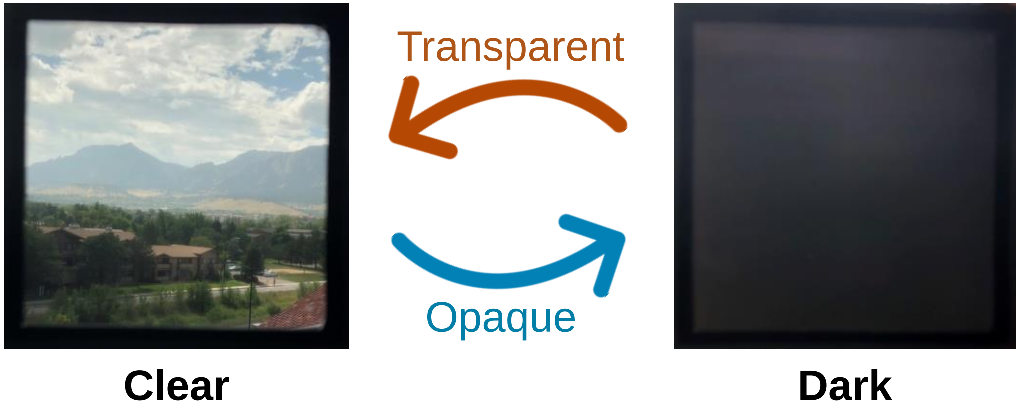
Metals are intrinsically stable

- No degradation from UV
- Chemically stable
- Easily electrodeposited from "green" solvents (i.e. H_2O)

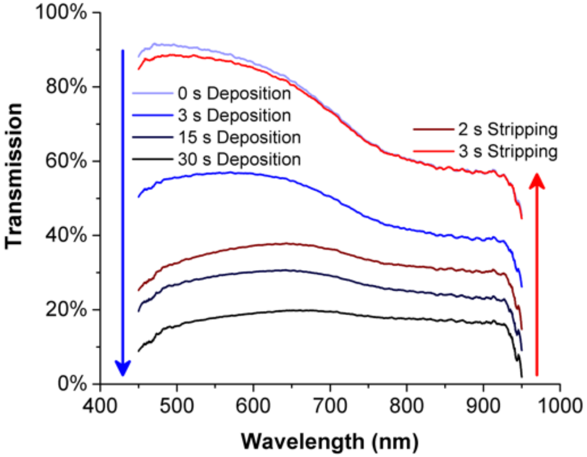
Potential for lower cost

- Solution-processed

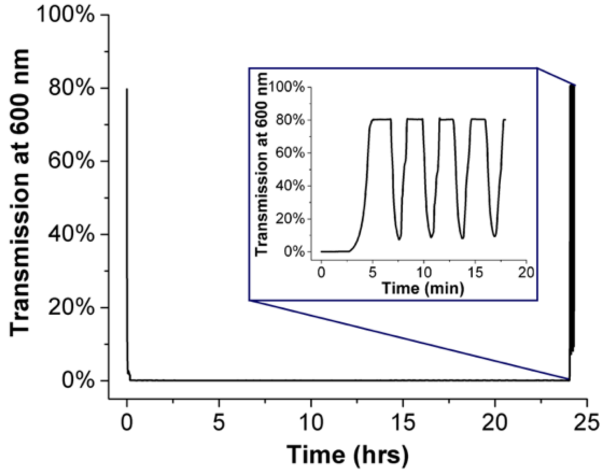




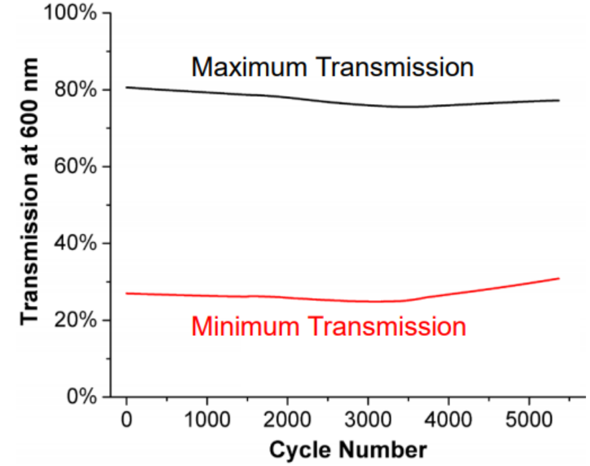
RME enables Fast Kinetics with Color Neutrality and Bistability over 1000s of Cycles



>60% Contrast in <1 minute



Zero power consumption in both states



>5000 cycles with minimal degradation

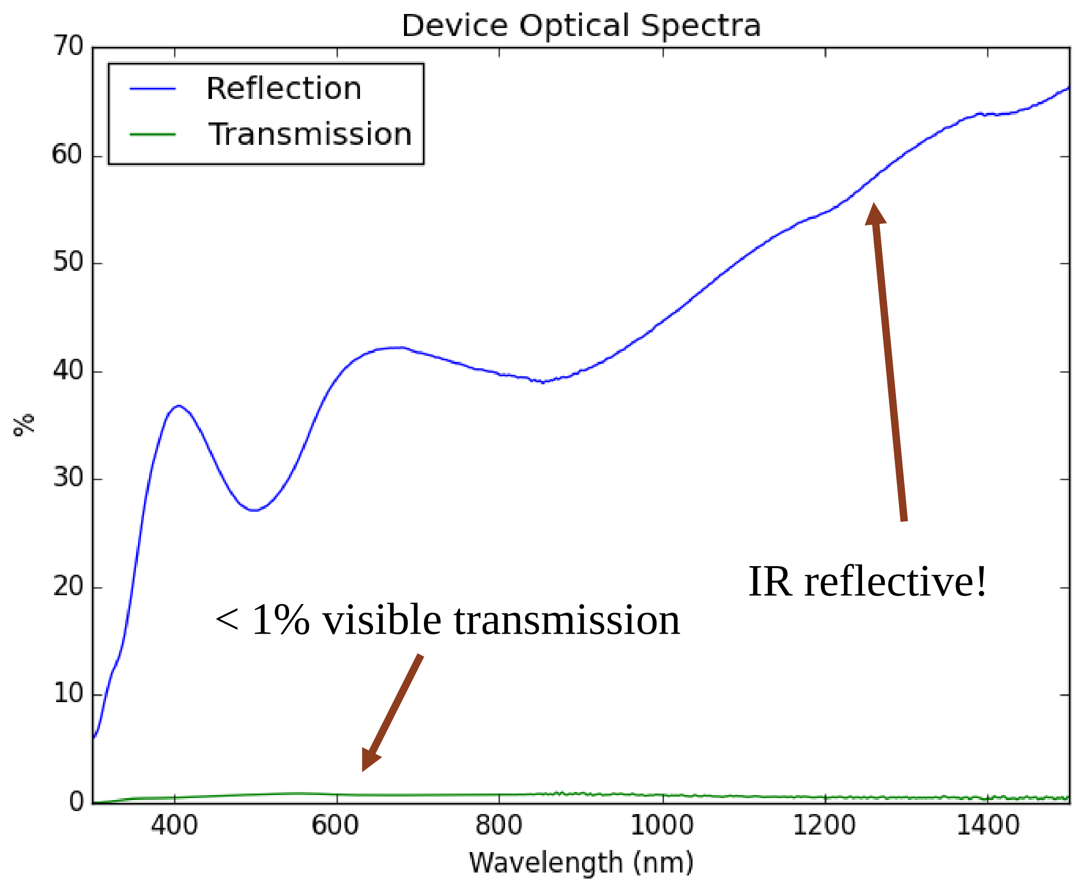
30 sec deposition

30 sec deposition

10 sec stripping

Largest dynamic range of any existing technology

- Can achieve < 0.1% transmission for privacy applications
- Reflects IR wavelengths for solar heat gain control

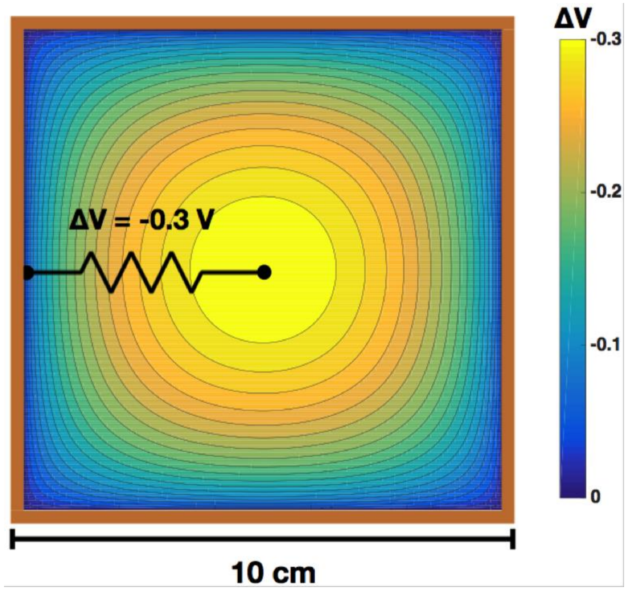


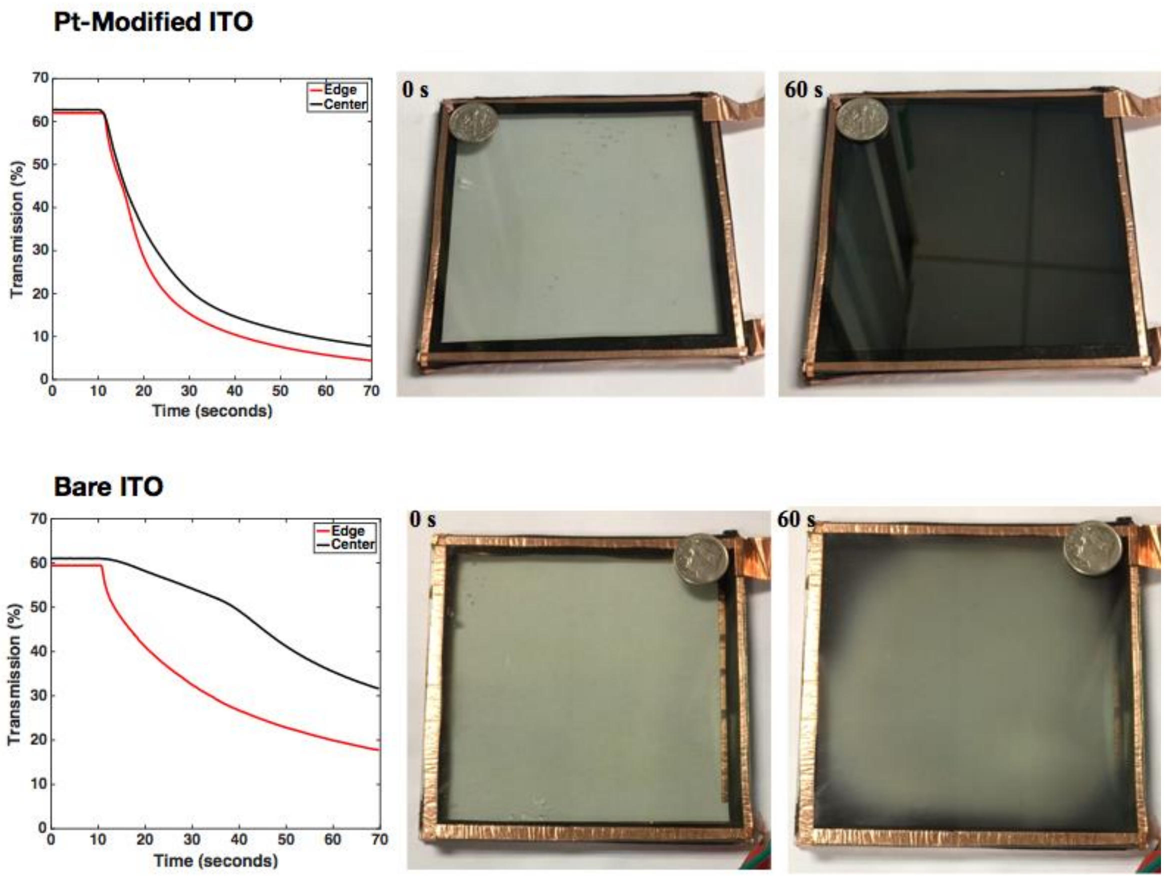
100 cm^2 devices that switch uniformly in 1 min.

$V_{applied}$

=

-600 mV





$$\Delta V = \frac{J\rho}{2t}\sqrt{(L^2 - x^2)(L^2 - y^2)}$$

Transmission < 5% in 1 minute!

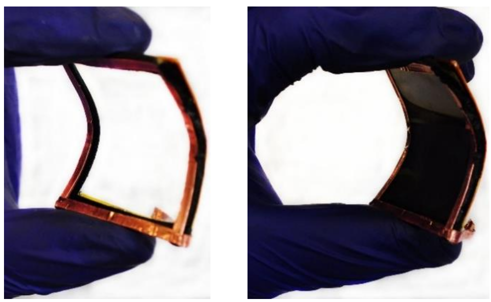
Source: Strand, M. T., McGehee, M. D., et al., *ACS Energy Letters, 3, 11, 2823-2828, 2018.*

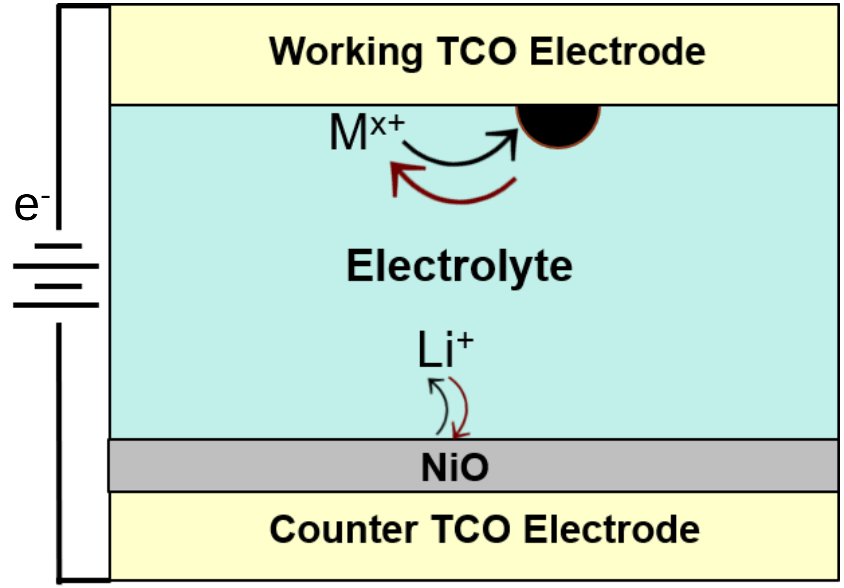
RME is Compatible with Traditional Ion-Intercalation Based Counter Electrode Materials

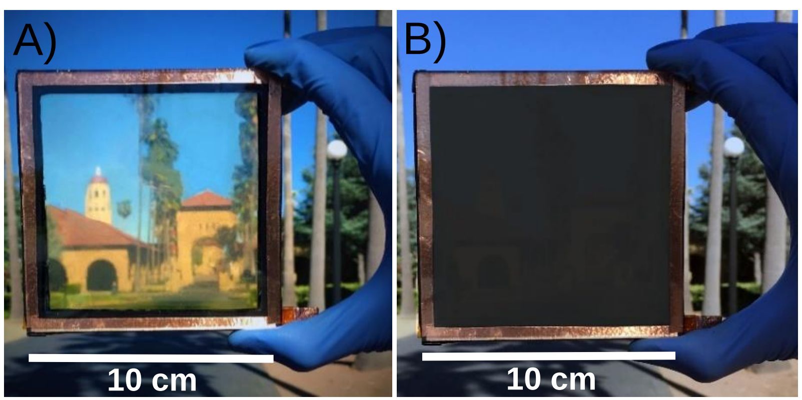
Working Electrode: $M^{x+} \rightleftharpoons e^-$ $M(s)$

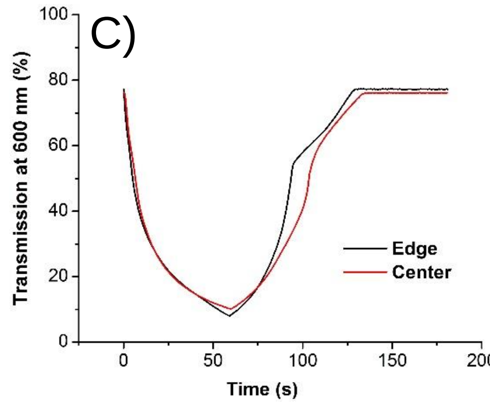
Counter Electrode: $Li_xNiO \rightleftharpoons NiO + x\,Li^+ + x\,e^-$

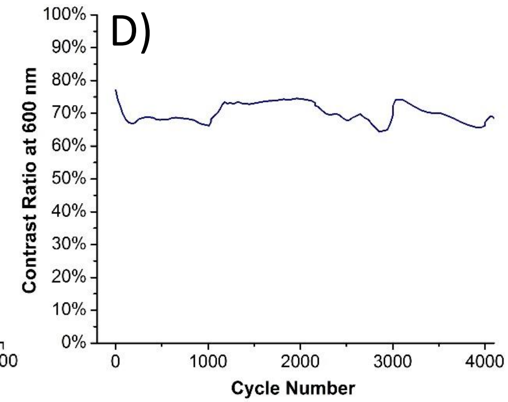
Potential Flexible Applications





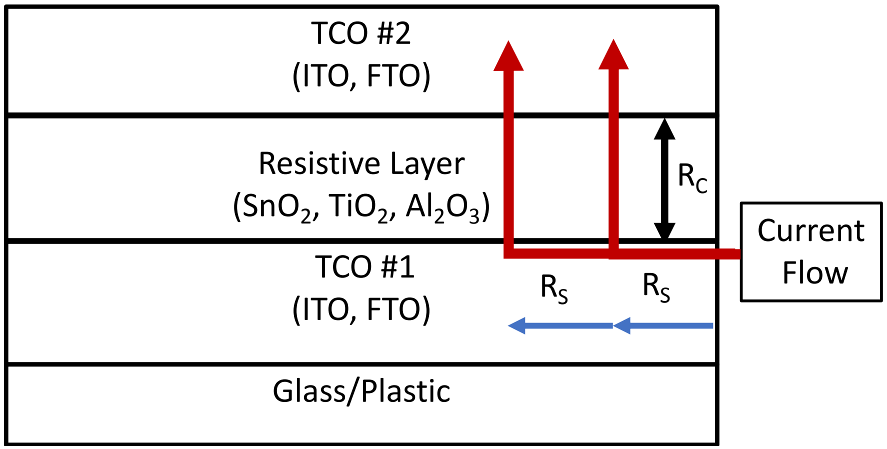


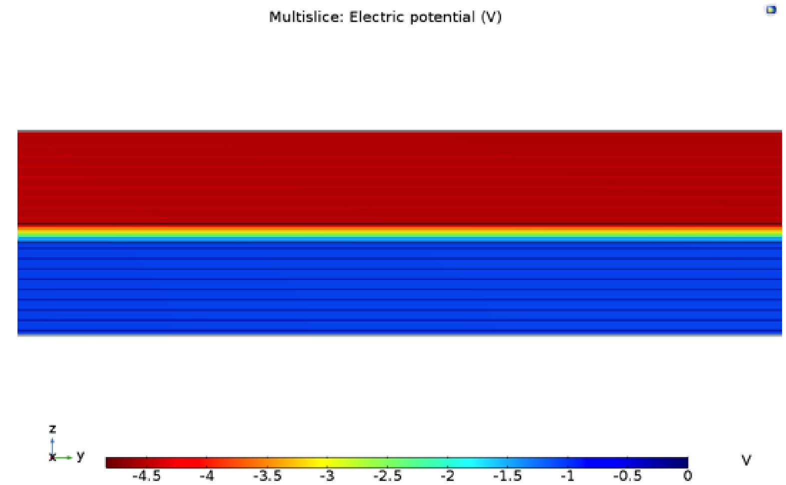


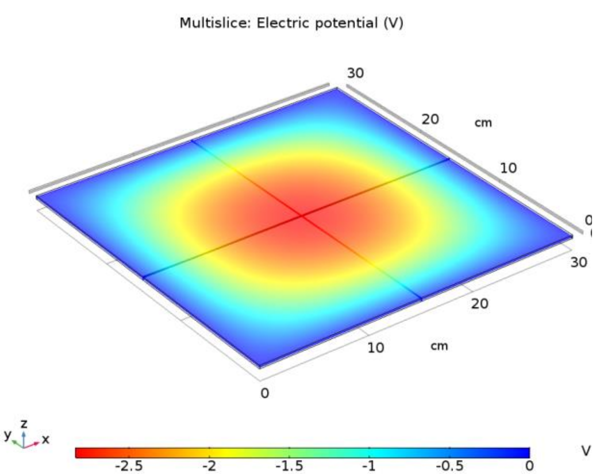


Uniform tinting on a $100cm^2$ scale with color neutrality and high contrast (~70%) in under a minute with no significant degradation over 4000 cycles

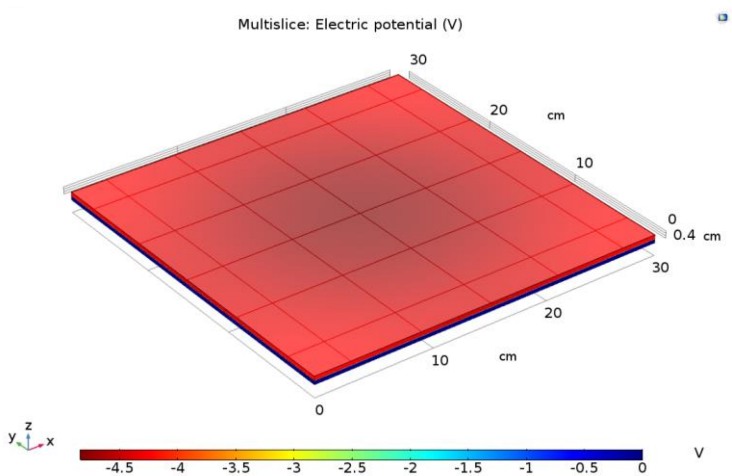
Cross-layer resistance for large-area switching.







ITO Only



3-Layer Electrode with Cross-Layer Resistance

12" X 12" Windows

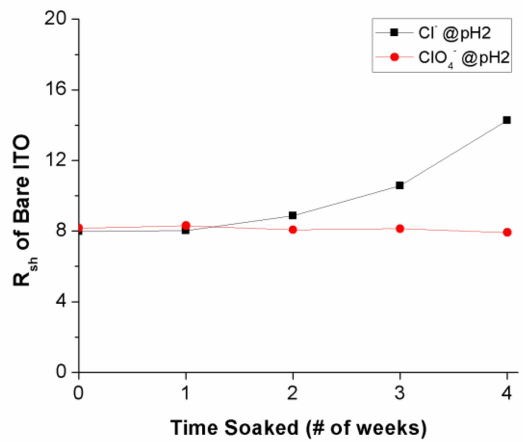
ClO_4^- Electrolyte for Improved Durability and Scale

Table I. The etch rate of ITO (V_e) in different etchants at 50°C. The K_A values given in the second column are constants for the first dissociation step at 25°C, from Ref. 15.

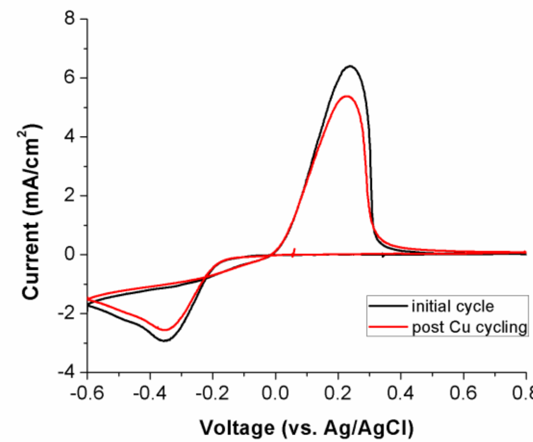
Etchant	K_A	V_e (nm/min)
6*M* CH_3COOH	1.8×10^{-5}	<0.1
6*M* H_3PO_4	1.1×10^{-3}	~0.3
2.2*M* HOOCCOOH[a]	5.9×10^{-2}	~0.3
6*M* HNO_3	21	2.0
6*M* H_2SO_4	$\sim 10^3$	~0.2
6*M* HCl	$\sim 10^7$	19
6*M* HBr	$\sim 10^8$	18
6*M* HI[b]	$\sim 10^9$	90
6*M* $HClO_4$	$\sim 10^9$	0
6*M* HCl + 0.1*M* I_2	—	33
6*M* HCl + 0.2*M* $FeCl_3$	—	50

[a] 2.2*M* is about the maximum solubility of HOOCCOOH in water.
[b] Contained a certain amount of I_2.

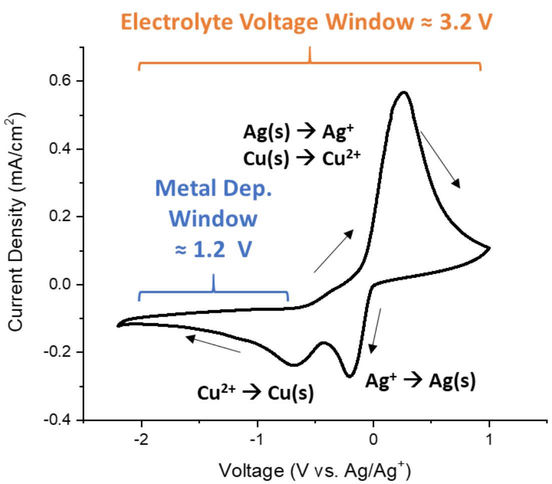
Scholten, M. *J. Electrochem. Soc.*, **1993**, 140, 2.

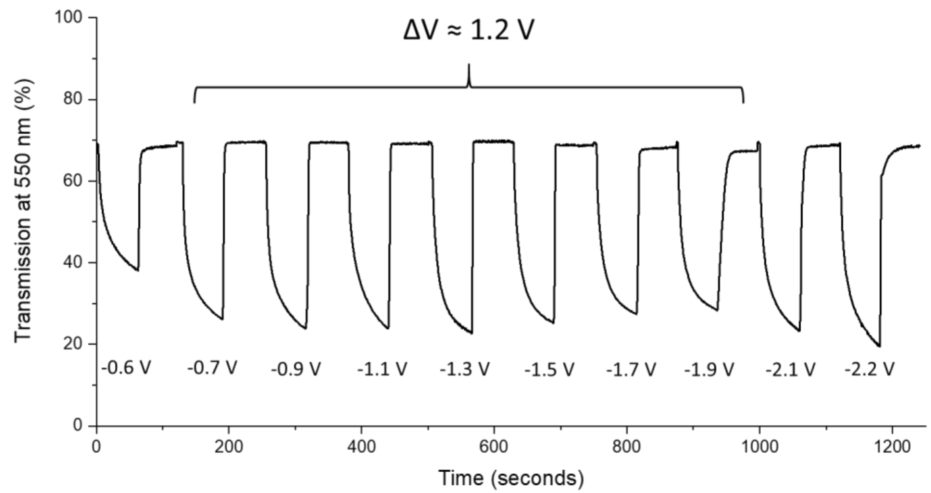


ClO_4^- Does Not Etch ITO



ClO_4^- is Stable After 1000s of Cycles





Propylene Carbonate Allows for Extended Voltage Window for Uniform Plating

Thank You

Stanford University, University of Colorado - Boulder
Professor Michael McGehee
michael.mcgehee@colorado.edu | (303) 492-2063

REFERENCE SLIDES

Project Budget

Project Budget: $410,689.00
Variances: Transferred grant from Stanford to University of Colorado-Boulder. Have not been able to spend money from grant in 2019.
Cost to Date: $84,026
Additional Funding: N/A

Budget History					
10/31/17– FY 2018 (past)		FY 2019 (current)		FY 2020 – 12/31/20 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$140,007	$17,488	N/A	N/A	N/A	N/A

Project Plan and Schedule

Project Schedule												
Project Start: 10/31/17		Completed Work										
Projected End: 12/31/20		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2018				FY2019				FY2020			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: 100 cm^2 device uniformity												
Q2 Milestone: Durable counter electrode												
Q3 Milestone: Electrolyte stability												
Q4 Milestone: Build cycling apparatus												
Current/Future Work												
Q3 Milestone: Build triple-layer electrodes												
Q4 Milestone: Demonstrate 10" x 10" device												