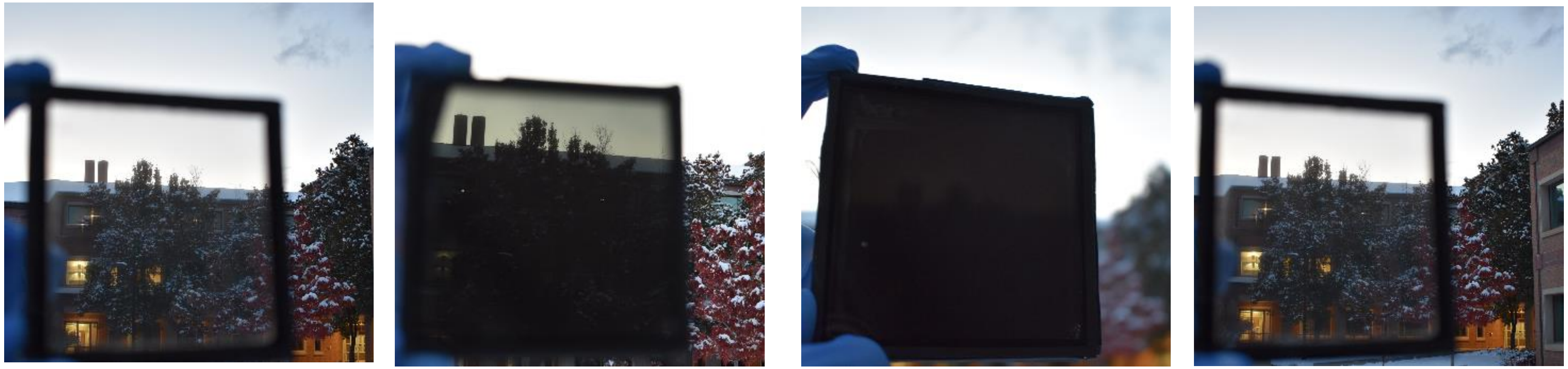
Robust Large-Scale Dynamic Windows using Reversible Metal Electrodeposition



University of Colorado Boulder, Stanford University
Professor Michael McGehee
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Project Summary

Timeline:

Start date: 10/31/17

Planned end date: 08/06/21

Key Milestones

1. Windows tint uniformly at 1 ft^2 scale, BP3
2. Incorporate start-up (TYNT Technologies) to commercialize the technology, raising $7M, BP3

Budget:

Total Project $ to Date:

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

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- DOE: $410,689
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Key Partners: We had discussions with more than 25 companies but did all of the work ourselves. We interact extensively with Professor Chris Barile at the University of Nevada Reno.

Project Outcome:

Our research group has engineering dynamic windows based on reversible metal electrodeposition with color neutral and uniform tinting up to 1 ft^2 (929 cm^2) scale with excellent durability (1,000 cycles). These windows employ a new electrolyte that drastically improves the shelf and cycle life. We have also added a polymer growth inhibitor that allows our windows to achieve privacy (residential) applications (<0.1% transmission). Finally, we have officially incorporated TYNT Technologies, a start-up intending to commercialize the technology and have raised $7M.

Dynamically tinted windows are the future

Visible light transmission | 10 % | 1 % | 0.1 % | True privacy

- Reduce heating, cooling and lighting costs by **20%** to save **$44 billion/year** in energy costs in the United States
- Look cleaner than blinds
- Reduce glare while maintaining views
- Provide privacy and the darkness people need to sleep better

Challenge

- *Neutral color*
- *Cost below $20/ft2*
- *Visible light transmission below 0.1 % to provide the privacy and ability to sleep that people want in their homes.*
- *Durable for 25-40 years*
- *Switches in under 10 minutes*

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, including TYNT Technologies
- Co-founder of TYNT Technologies

Tyler S. Hernandez

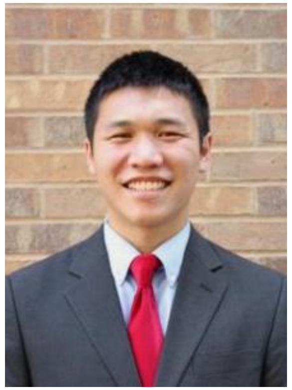
- Inorganic Chemistry Ph.D.
- Research Projects/Interests
  - Reversible, aqueous electrolytic systems
  - Gel electrolyte systems with high stability and reversibility for RME dynamic window applications
- NSF Fellowship
- Co-founder of TYNT Technologies

Michael T. Strand

- Materials Science & Engineering Ph.D.
- Research Projects/Interests
  - Device modelling and electrode design
  - Scaling RME windows to commercial size
  - Electrolyte additives for enhanced optics
- NSF Fellowship, Stanford Graduate Fellowship
- Co-founder of TYNT Technologies

Andrew L. Yeang

- 4th year Chemical Engineering Ph.D. Candidate
- Research Projects/Interests
  - Metal mesh electrode design with high capacity, high reversibility, low haze, and high transparency
  - Mechanical stress and strain in electrodeposited films
- GAANN Fellowship



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

Conventional technologies have drawbacks

	Tungsten Oxide Electrochromics	Reversible Metal Electrodeposition	Motorized blinds
Companies	View, Sage, Kinestral	Tynt	e.g. Hunter Douglas
Color	Slightly blue	Perfectly neutral	The view is lost
Highest light transmission	60 %	75 %	90 %
Lowest light transmission	1 %	0 %	0 %, but light gets in around edges
Cost	$\$50/ft^2$	Path to $\$10/ft^2$	$\$90/ft^2$
Fabrication	Deposit at high temperature	Blade coat in roll-to-roll coater	Weave
Retrofittable	No	Yes	Yes

Reversible Metal Electrodeposition (RME) for Dynamic Windows

Metals are great attenuators of light

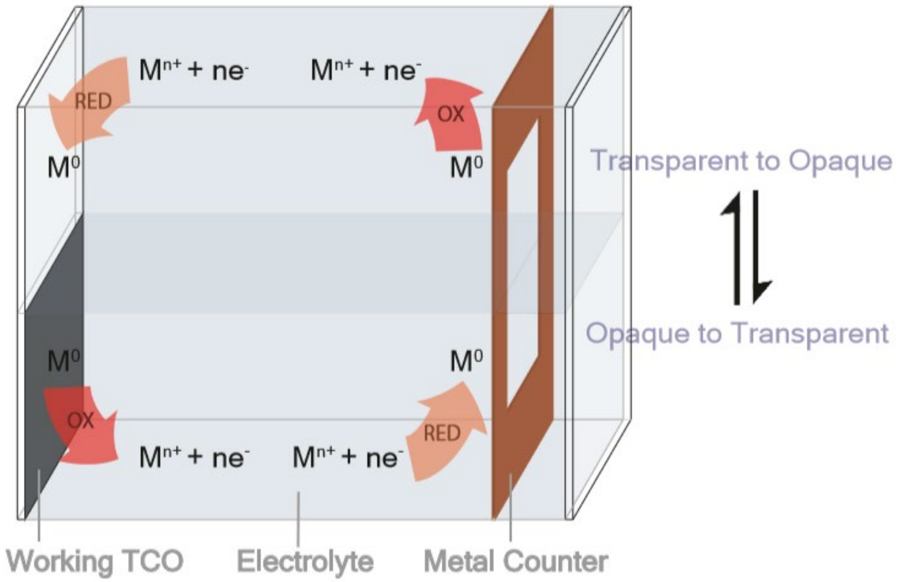
- Completely opaque at 20-30 nm thickness
- Reflective or absorptive (mirror or black)
- Can achieve <0.1% transmission (privacy applications)

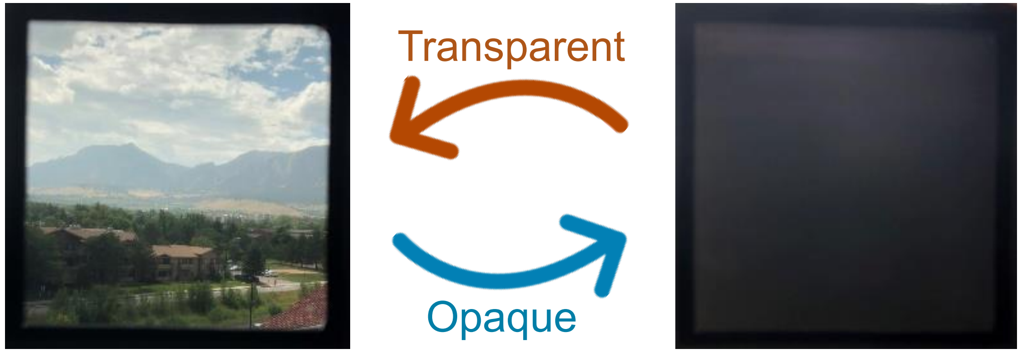
Metals are intrinsically stable

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

Potential for lower cost

- Solution-processed



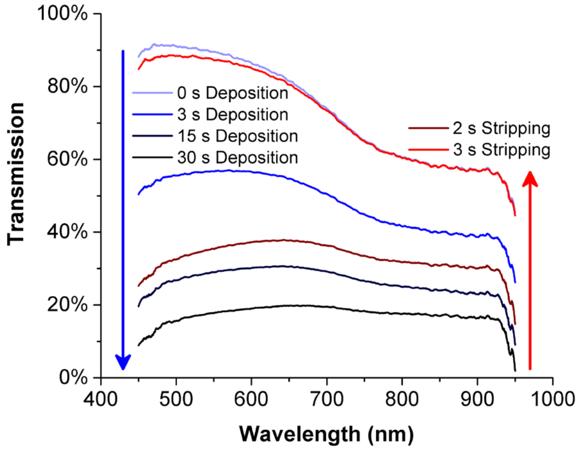


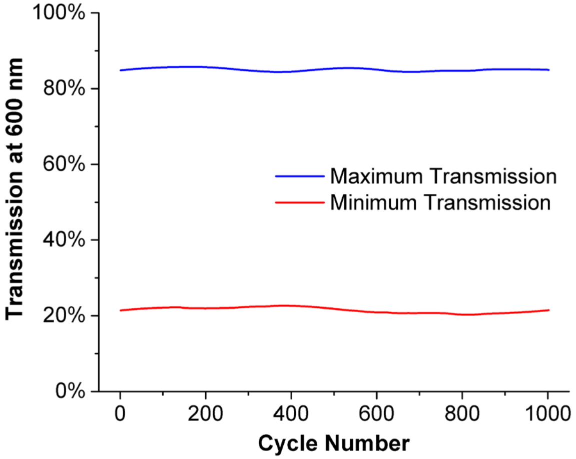
Clear

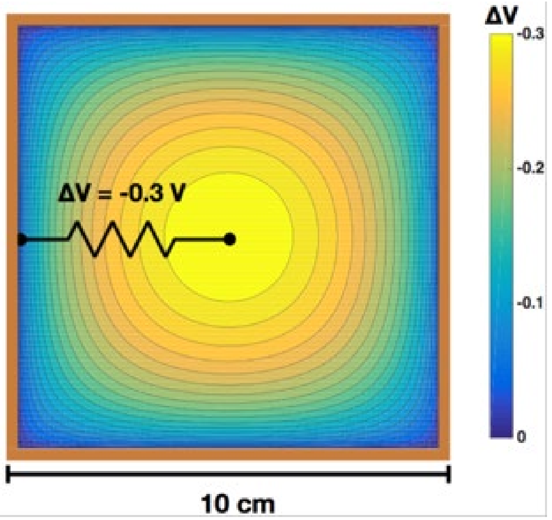
Dark

Generation 1 RME Windows

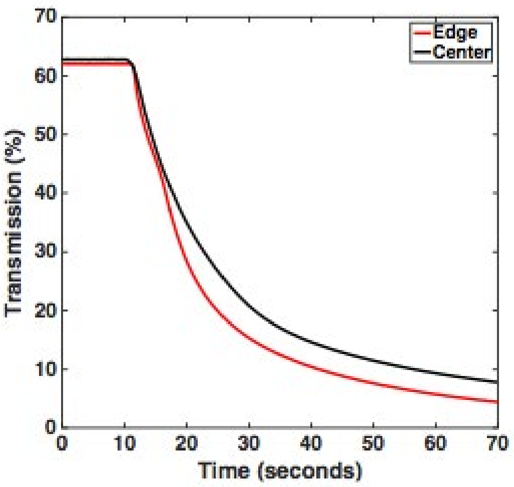
RME Windows with fast, uniform, and color neutral switching over 1,000 cycles at a 100 cm^2 scale!







Pt-Modified ITO



ClO_4^- Electrolyte Improves Durability – Both Shelf and Cycle Life

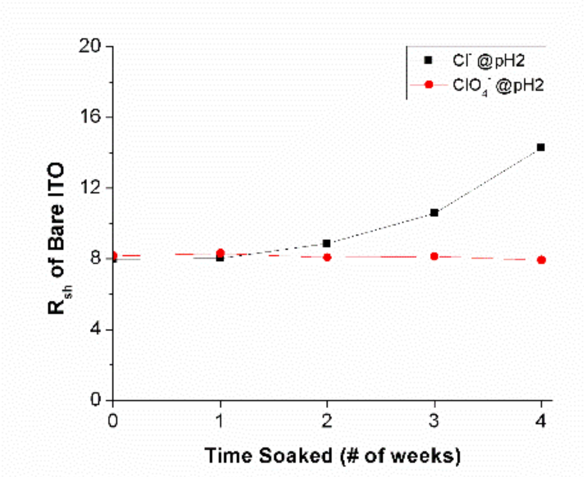
ClO_4^- Does Not Etch ITO!

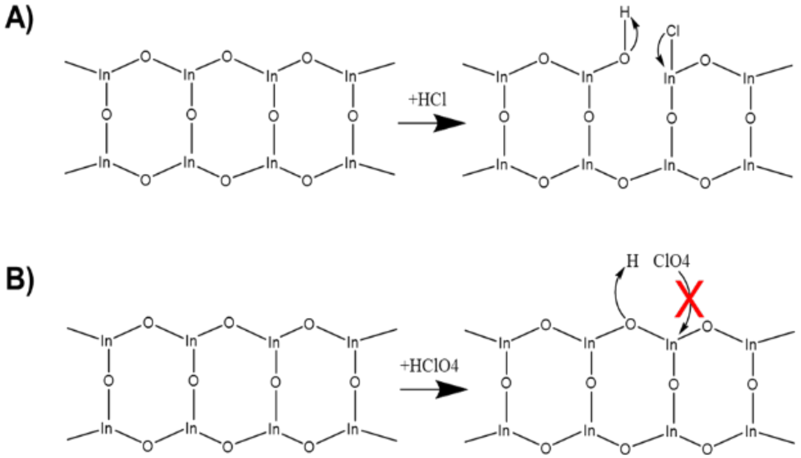
Table I. The etch rate of ITO (V_e) in different etchants at 50°C. The K_A values given in the second column are constants for the first dissociation step at 25°C, from Ref. 15.

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^{-2}	~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

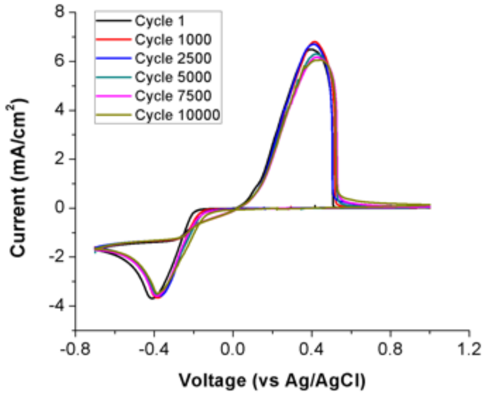
[a] 2.2*M* is about the maximum solubility of HOOCCOOH in water.
[b] Contained a certain amount of I_2.

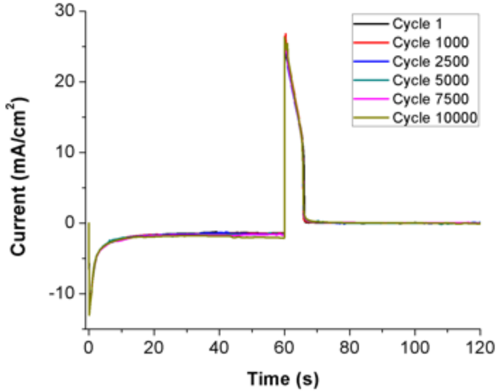
Scholten, M. *J. Electrochem. Soc.*, **1993**, 140, 2.

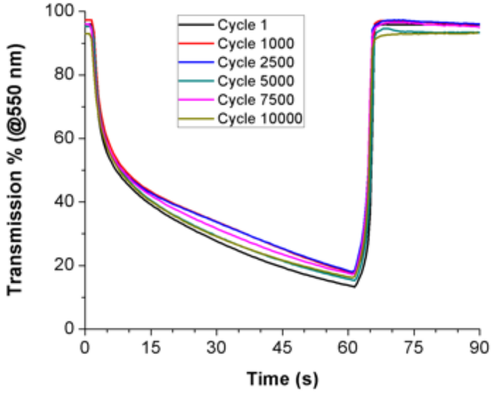




ClO_4^- Electrolyte Maintains High Coulombic Efficiency and >70% Contrast Ratio in <1 min switching over 10,000 cycles!

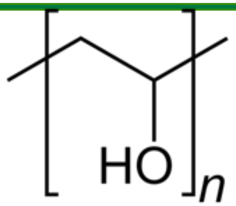




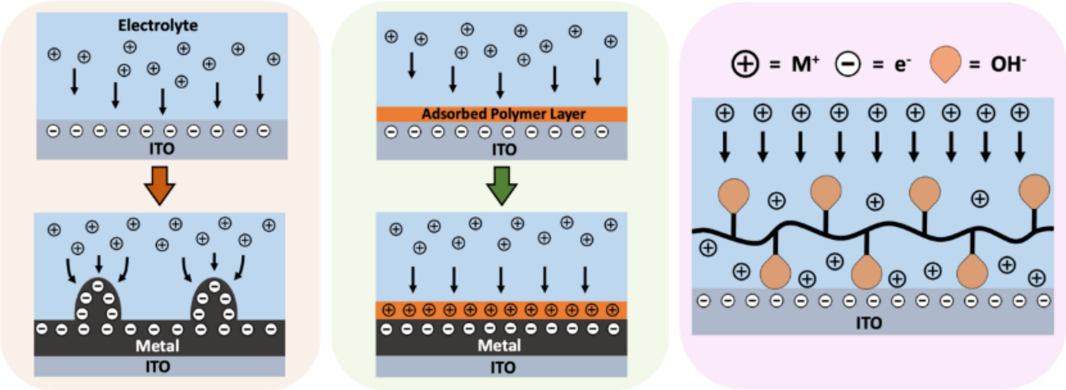


Polymer Additive (PVA) Enhances Optical Contrast and Scale

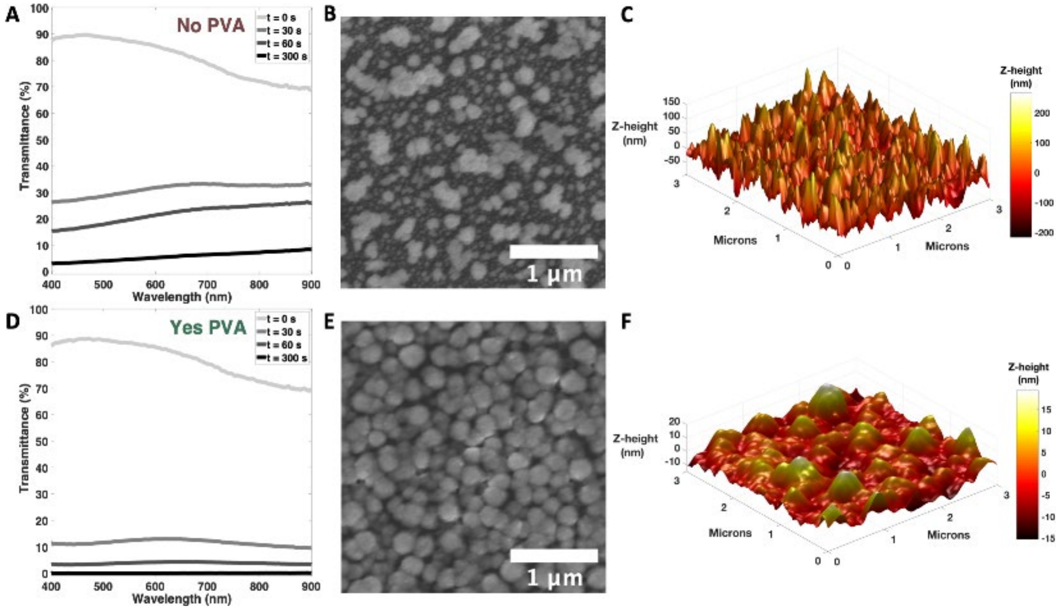
Polymers used to grow smoother and denser metal films



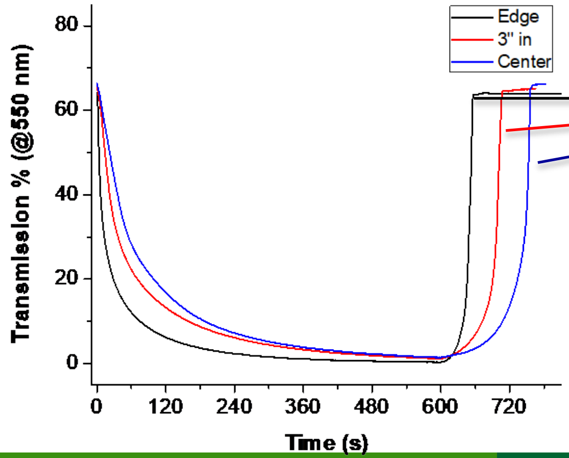
Polyvinyl (alcohol) or PVA

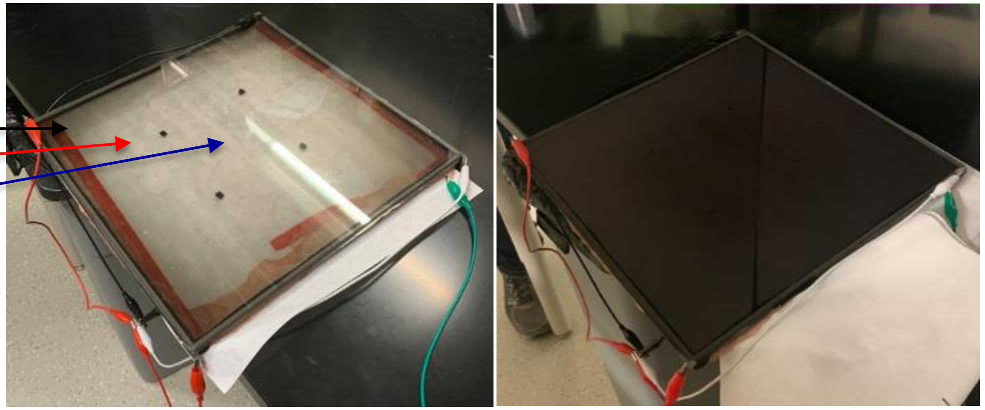


High metal deposit density improves optical contrast (<10^{-5} VLT)

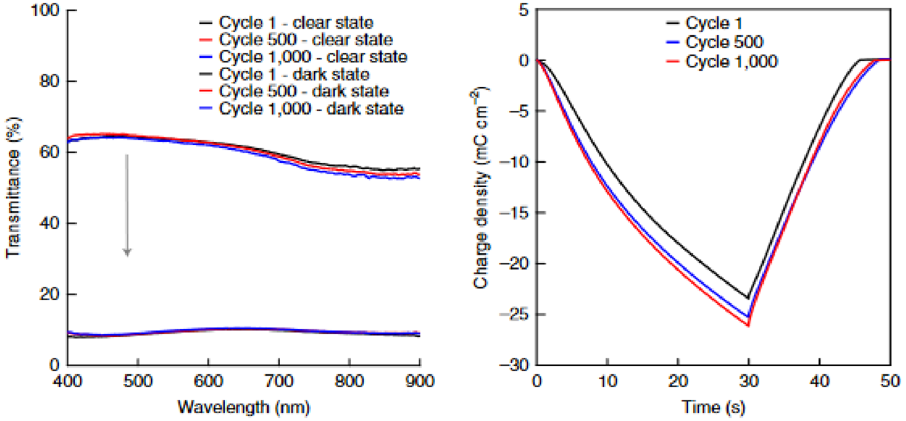


Uniform tinting over 1 ft^2 device with <1% min T, >60% max T

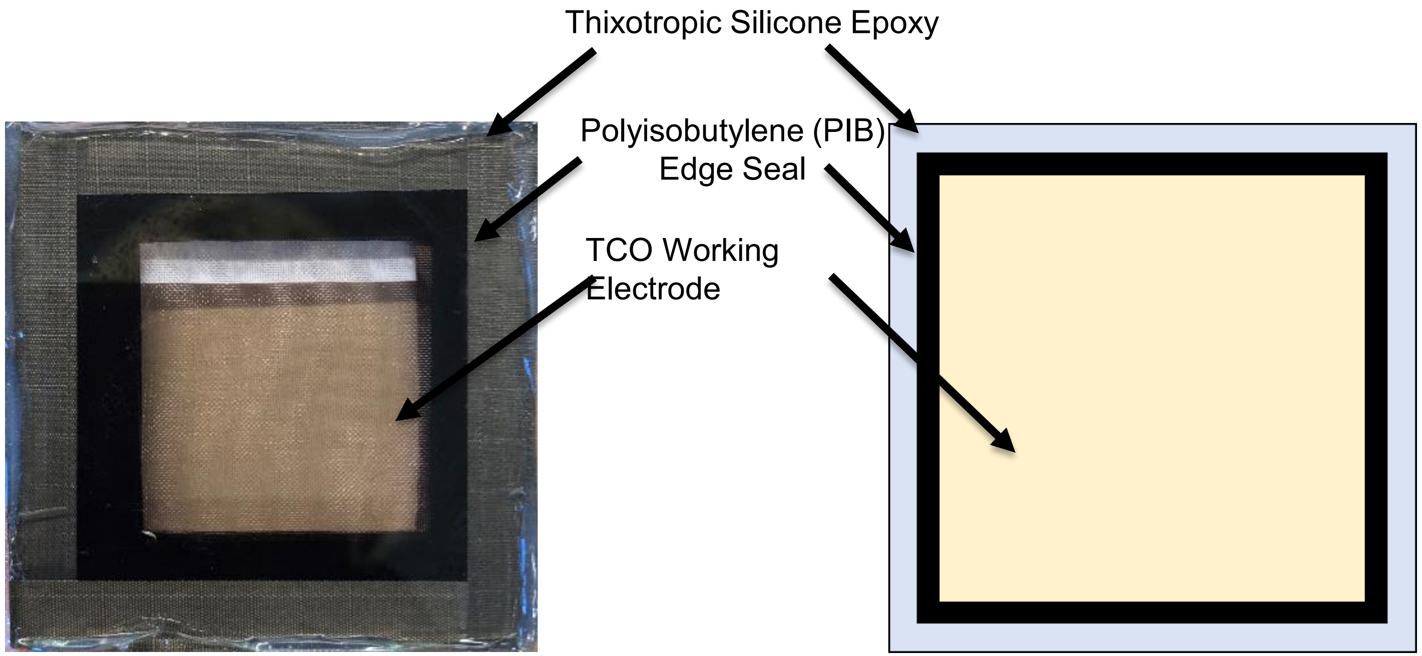




Switching in <1 min over 1,000 cycles



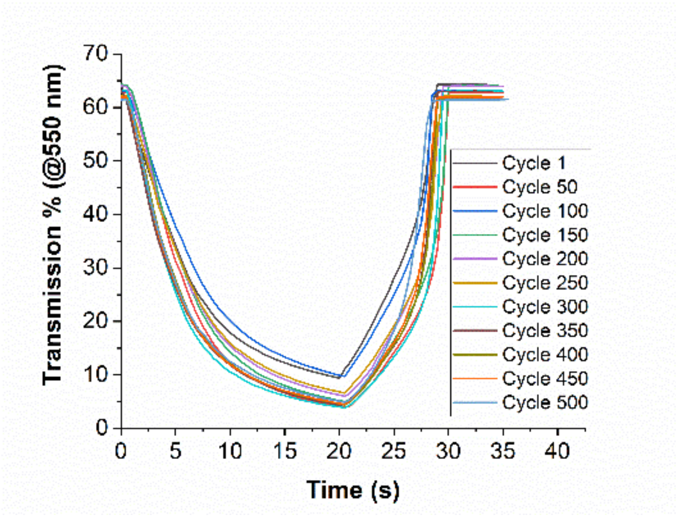
ASTM Durability Testing Underway

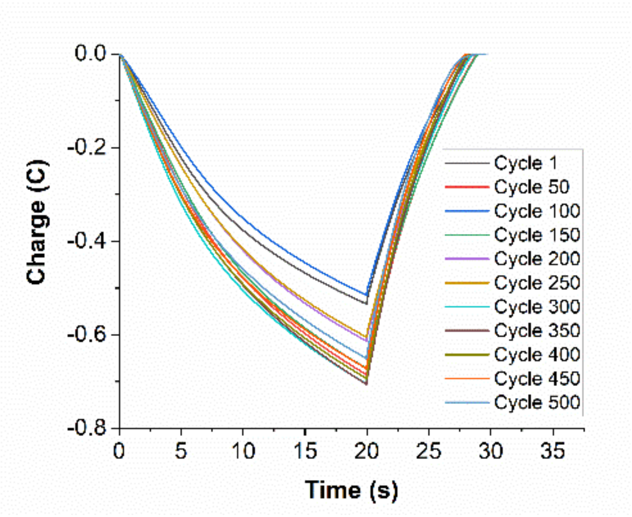


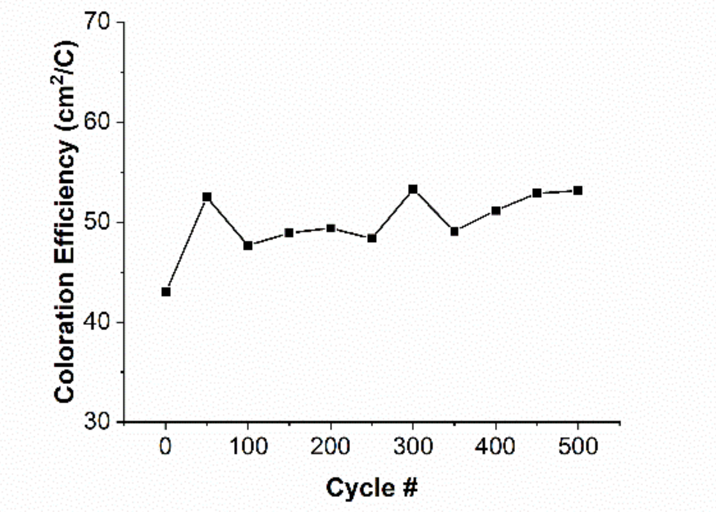
- > 50,000 cycles for clear to dark
- 1 sun illumination
- 85 degrees C

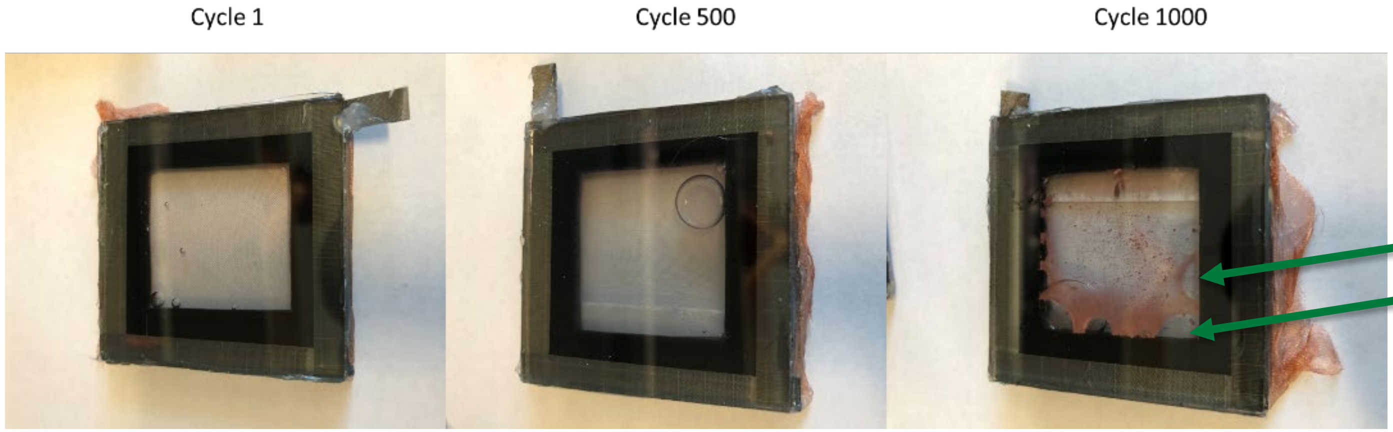
500 cycles at ASTM conditions

500 cycles with no degradation in contrast or switching speed, >99% Coulombic Efficiency, and consistent Coloration Efficiency



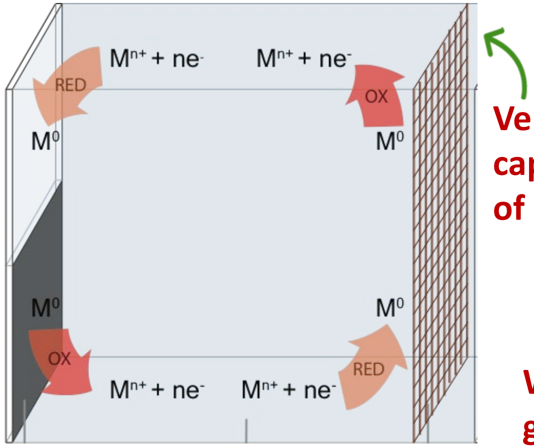






- Air bubbles form from electrolyte outgassing at elevated temperature and UV exposure
- Liquid/gas interface causes metal irreversibility issues

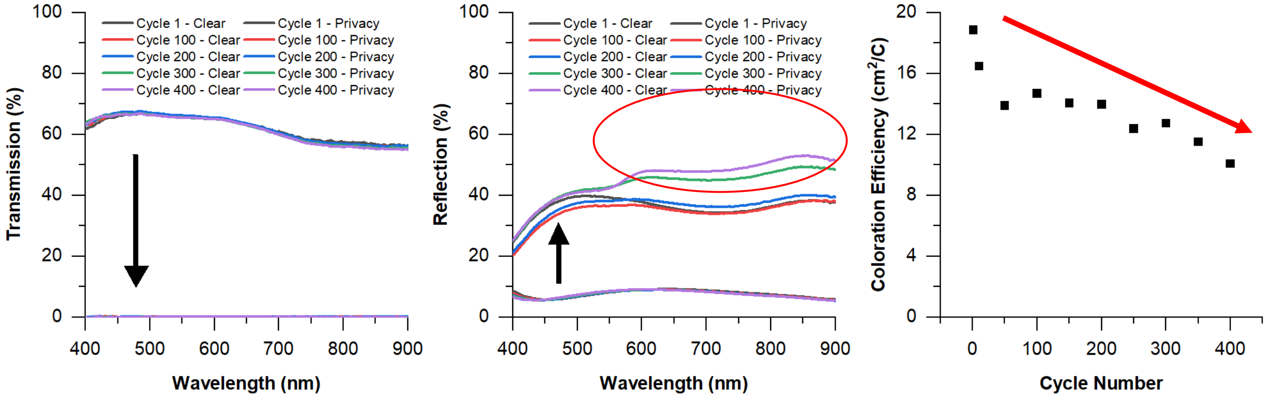
Improved Metal Mesh for Durable Privacy (<0.1% T) Cycling



Very high capacity/source of metal ions

When a lot of copper is removed from the grid, the Cu:Bi ratio becomes too high.

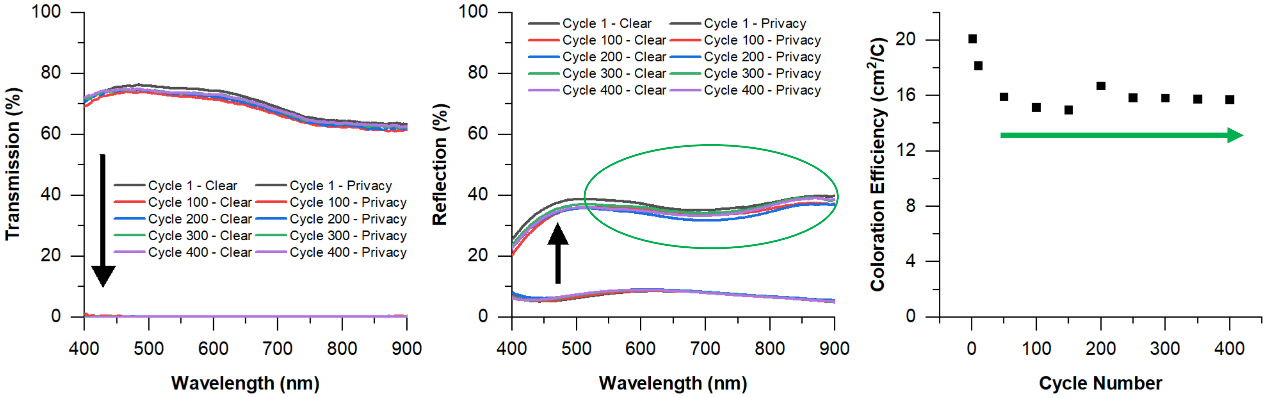
Cu Mesh -> increases [Cu^{2+}] -> increase in reflection and decrease in coloration efficiency



We have shared the design with Marc Lafrance, but cannot reveal it publicly until we file a patent.

An additional improvement to the electrolyte has also improved durability and will also be patented soon. The photos you saw have the improved electrolyte. The video is at www.tynt.io.

Improved Mesh -> consistent in reflection and coloration efficiency



Project Impact

- 6 Publications in high-impact journals (see below)
- 4 Provisional Patents
- Spun out TYNT Technologies to commercialize the technology
- Won $125 K from the Lab Venture Challenge

1. "Polymer Inhibitors Enable >900 cm^2 Dynamic Windows Based on Reversible Metal Electrodeposition with High Solar Modulation," M.T. Strand, T.S. Hernandez, M.G. Danner, A.L. Yeang, N. Jarvey, C.J. Barile, M.D. McGehee, *Nature Energy*, (2021) DOI: https://doi.org/10.1038/s41560-021-00816-7
2. "Electrolyte for Improved Durability of Dynamic Windows Based on Reversible Metal Electrodeposition," T.S. Hernandez, M. Alshurafa, M.T. Strand, A.L. Yeang, M.G. Danner, C.J. Barile, M.D. McGehee, *Joule,* (2020) DOI: 10:1016/j.joule.2020.05.008.
3. "Hybrid Dynamic Windows Using Reversible Metal Electrodeposition and Ion Insertion," S.M Islam, T.S. Hernandez, M.D. McGehee and C.J. Barile, *Nature Energy*, 4 (2019) 223-229.
4. "Factors that Determine the Length Scale for Uniform Tinting in Dynamic Windows Based on Reversible Metal Electrodeposition," M.T. Strand, C.J. Barile, T.S. Hernandez, T.E. Dayrit, L. Bertoluzzi, D.J. Slotcavage, M.D. McGehee, *ACS Energy Letters*, 3 (2018) 2823-2828.
5. "Bistable Black Electrochromic Windows Based on the Reversible Metal Electrodeposition of Bi and Cu," T.S. Hernandez, C.J. Barile, M.T. Strand, T.E. Dayrit, D.J. Slotcavage, M.D. McGehee, *ACS Energy Letters*, 3 (2018) 104-111.
6. "Dynamic Windows with Neutral Color, High Contrast, and Excellent Durability using Reversible Metal Electrodeposition," C. J. Barile, D. J. Slotcavage, J. Hou, M. T. Strand, T. S. Hernandez, M. D. McGehee, *Joule* 1 (2017) 133.

Incorporation of TYNT Technologies

TYNT

• SMART WINDOWS FOR THE HOME

CEO: Ameen Saafir (Ameen@tynt.io)

$7 M seed round closed on 7/30/21

Strategic partnership with a major company that can deploy our dynamic glazings.

Prime Impact Fund

STARLIGHT VENTURES

www.tynt.io

TYNT

Ameen K. Saafir

CEO

Former Kinestral Chief Engineer.
16 years at Samsung, Dupont and Kinestral

John Dwyer

COO/CPO

Ran Wearables business at Flextronics, products include
Nike FuelBand, Chromecast, and Wink Hub.

Michael McGehee

Chief Scientist

Materials Science Professor at Colorado.
#11 Materials Scientist in world for scientific impact. Advised 7 companies, 215 Publications, 13 Patents.

Tyler Hernandez

Materials Development

Inorganic Chemistry PhD
Developed electrolyte chemistry.

Michael Strand

Process Development

Materials Science & Engineering PhD
Developed electrode system.

Taylor Aviles

Business Development

Former Corporate Strategy at Kinestral.

Thank You

We love this project and could not have done it with the DOE's support.

University of Colorado Boulder, Stanford University

Professor Michael McGehee

michael.mcgehee@colorado.edu | (303) 492-2063

REFERENCE SLIDES

Project Plan and Schedule

Project Schedule	
Project Start: 10/31/17	Completed Work
Projected End: 12/31/20	Active Task (in progress work)
*note change in Q dates due to move in summer 2018 from Stanford to Colorado	Milestone/Deliverable (Originally Planned)
	Milestone/Deliverable (Actual)

	FY2019				FY2020				FY2021			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Dec)	Q1 (Jan-Mar)	Q2 Apr-June)	Q3 (Jul-Sept)	Q4 (Oct-Dec)	Q1 (Jan-Mar)	Q2 Apr-June)	Q3 (Jul-Sept)	Q4 (Oct-Dec)
Past Work												
Q1 Milestone: 100cm^2 devices switch <1 min												
Q2 Milestone: Electrolyte+packaging stability												
Q3 Milestone: Gridline transparency and haze												
Q4 Milestone: Window with 5,000 cycles												
Q1 Milestone: Fabricate 1 ft^2 window												
Q4 Milestone: Commercial Partnerships												
Current/Future Work												
Q4 Milestone: Device durability												

Project Budget

Project Budget: $410,689.00
Variances: Transferred grant from Stanford to University of Colorado-Boulder.
Cost to Date: All DOE funds are spent.
Additional Funding: VentureWell E-Teams Program ($5K), Lab Venture Challenge $125 K.

Budget History					
10/31/17 – FY 2019 (past)		FY 2020 (current)		FY 2021 – Insert End Date (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$355,586	$54,054	$86,259	15,590		