LOW COST VOLTAGE-CONTROLLED WINDOW CAN BE TUNED TO BLOCK VISIBLE AND/OR INFRARED LIGHT

PROJECT IMPACT SHEET

PROJECT TITLE: Low Cost Solution Processed Universal Smart Window Coatings
PROGRAM: OPEN 2012
AWARD: $4,730,970
PROJECT TEAM: University of Texas, Austin (Lead); Heliotrope, Inc.; LBNL
PROJECT TERM: March 2013 – September 2016
PRINCIPAL INVESTIGATOR (PI): Dr. Delia Milliron

TECHNICAL CHALLENGE
Each year about 2.5 quads of primary energy is expended for air conditioning to counteract the heat entering through windows from sunlight. Electrochromic (EC) windows, that can be tuned to block light transmission using an applied voltage, are now available commercially as options in sealed double pane window units. However they have not reached significant market implementation due in large part to high cost, typically around $50/ft². These window panes are typically manufactured via vacuum deposition techniques, and modulate the broad spectrum of sunlight from the visible through the near-infrared (NIR). Realistic operation of these devices in the highest-value applications is expected to save 0.6 quads annually over baseline static windows. In addition to the high cost, a barrier to the use of these windows is the reduction of useful visible light (daylighting) when they are darkened to block heat transmission. Newer technologies are needed that can demonstrate a marked improvement in optical performance, cycling stability, switching speed, and a significant reduction of manufacturing cost to be competitive with inexpensive static coatings (~$3-5/ft² for the coating alone).

TECHNICAL OPPORTUNITY
Advances in materials science have created new approaches to the fabrication of coating with EC properties. Switching to nanostructured composite EC materials opens up solution-based deposition techniques that could lower the cost of electrochromic window fabrication by about 40% compared to conventional ECs. Furthermore, the recent discovery of a plasmonic EC effect present in some novel nanocomposites allows for independent management of NIR and visible light transmittance. This could enable independent control of visible and IR light carrying heat into building spaces and could save up to an additional 0.1 quads.

INNOVATION DEMONSTRATION
Prior to ARPA-E support, the project team had demonstrated a prototype “dual-band” EC material, able to independently modulate visible and NIR light transmission\(^1\). Early experiments combined indium tin oxide (ITO) nanocrystals within a Nb\(_2\)O\(_5\) nanocrystals.

polyoxometalate (POM) cluster-derived matrix. The device (Figure 1) could transition to a “cool” state via the application of modestly negative voltages, resulting in a ~65% decrease in NIR transmission (T\textsubscript{NIR}) while maintaining visible light transmission (T\textsubscript{VIS}) at ~96%, reducing solar heat gain but allowing daylighting. Applying a more negative voltage decreases the T\textsubscript{VIS}, transitioning the window into a “dark” state much like a traditional EC window. These states are end points on a continuum of optical states accessible via intermediate voltages.

The project team goals were to develop devices based on these materials approaches, with improved optical properties, switching speed, and durability. Most significantly, the project focused on scaling up fabrication of devices from 4 cm\textsuperscript{2} to 25 cm\textsuperscript{2} using a lower-cost, higher-throughput solution-processable technique (such as spray coating) to fabricate all three major components of the device: the electrochromic electrode, the counter electrode, and the electrolyte. The targets for these films included demonstrating +/-5% film uniformity, <15 min switching time, 30% T\textsubscript{NIR} modulation while maintaining T\textsubscript{VIS} at >50%, and cycling the transitions at least 100 times. Accomplishing these challenging targets required rethinking the materials set at the beginning of the project to allow the use of scalable solution-processable techniques.

The team found the maximum achievable T\textsubscript{NIR} with the original ITO/Nb\textsubscript{2}O\textsubscript{5} materials set to be fundamentally limited. They identified a new materials set, CsWO\textsubscript{x}/ITO, and demonstrated substantially improved T\textsubscript{NIR} and T\textsubscript{VIS} values and switching speeds. When coupled with the team’s parallel work on the counter electrode and electrolyte, the EC devices demonstrated performance that surpassed the end-of-project solid-state device targets including the reduced switching time.

Simultaneous efforts at Heliotrope focused on translating the materials and devices to solution-processed manufacturing techniques. The team overcame two significant challenges. First, they were able to reliably charge the devices at the outset via a built-in electrochemical reaction. Second, they were able to fabricate ~100 cm\textsuperscript{2} devices with blade coating. It is expected that either this manufacturing technique or curtain coating will readily transfer to a pilot production line or larger.

Having achieved many of the original technical targets, the team began working to ensure durability against UV degradation, long-term cycle life, and reduce the slightly off-neutral coloration observed in some of the states. Mixtures of the tungsten oxide with niobium oxide materials were found to be significantly more color neutral than pure WO\textsubscript{3} or Nb\textsubscript{2}O\textsubscript{5} devices. Further improvements in coloration, switching speed, durability, and spectral transmission of the three states were realized by fabricating a templated mesoscale architecture of WO\textsubscript{x} nanocrystals and infilling the pores with NbO\textsubscript{x}.

**PATHWAY TO ECONOMIC IMPACT**

The promise of the project team’s technology has been recognized through investment by Prelude Ventures, receipt of an R&D 100 award in 2013, selection for $1M in Small Business Innovation Research (SBIR) funding in 2014, and selection for $250k of funding through the Wells Fargo Innovation Incubator program.

The team is now working on transitioning the the dual-band window technology to a commercial product. The window market is highly sensitive to coloration and requires long-term durability. The team is currently experimenting with variants of their successful chemistries to achieve improved coloration and durability, and is also carrying out environmental stress testing to identify and mitigate the deleterious effects of long-term aging.

In parallel, the team is using the new solution-processed techniques to manufacture single-band EC windows that have the potential to be fabricated at a significantly lower cost than incumbent vacuum deposition technologies. The Heliotrope team estimates an installed actual selling price significantly less than the ~50/ ft\textsuperscript{2} for competing products, and a near 7x reduction in capital costs for manufacturing equipment. The team has established agreements with window fabricators to produce or sell EC panes rather than competing directly with full insulated glazing unit (IGU) window assembly manufacturers.

The Heliotrope team plans to establish itself in the EC window market with a single band product while work continues to improve the coloration, speed, and durability of the dual-band window. The first market for the dual band window may be in higher value “stepping-stone” product offerings such as vehicular windows, skylights, or sunroofs.
LONG-TERM IMPACTS

The team's work has demonstrated the commercial promise of an entirely new approach to creating controllable window coatings, with a resulting cost reduction that has the potential to enable the projected U.S. energy savings of up to 0.6 quads using electrochromic windows in certain climate areas. Further advances based on this new approach may yield significantly improved control of optical properties with expanded applications and associated further energy savings.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of September 2016, the Heliotrope team’s project has generated three invention disclosures to ARPA-E, three U.S. Patent and Trademark Office (PTO) patent applications and two issued patents:

**Patents**


The team has also published the scientific underpinnings of this technology extensively in the open literature.

**Publications**


