

**SERI/TP-212-3786  
UC Category: 316  
DE90000335**

# **Electrochromic Sun Control Coverings for Windows**

**D. K. Benson  
C. E. Tracy**

**April 1990**

Prepared for the  
Society of Vacuum Coaters  
33rd Annual Technical Conference  
New Orleans, Louisiana  
April 29 - May 4, 1990

**Prepared under task number SB013051**

**Solar Energy Research Institute**  
A Division of Midwest Research Institute

1617 Cole Boulevard  
Golden, Colorado 80401-3393

Prepared for the  
**U.S. Department of Energy**  
Contract No. DE-AC02-83CH10093

## NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Printed in the United States of America  
Available from:  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Road  
Springfield, VA 22161

Price: Microfiche A01  
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

# ELECTROCHROMIC SUN CONTROL COVERINGS FOR WINDOWS

D.K. Benson and C.E. Tracy  
Solar Energy Research Institute  
Golden, Colorado USA

## ABSTRACT

The 2 billion square meters (m<sup>2</sup>) of building windows in the United States cause a national energy drain almost as large as the energy supply of the Alaskan oil pipeline. Unlike the pipeline, the drain of energy through windows will continue well into the 21st century. A part of this energy drain is due to unwanted sun gain through windows. This is a problem throughout the country in commercial buildings because they generally require air-conditioning even in cold climates. New commercial windows create an additional 1600 MW demand for peak electric power in the United States each year.

Sun control films, widely used in new windows and as retrofits to old windows, help to mitigate this problem. However, conventional, static solar control films also block sunlight when it is wanted for warmth and daylighting. New electrochromic, switchable, sun-gain-control films now under

development will provide more nearly optimal and automatic sun control for added comfort, decreased building operating expense, and greater energy savings.

Switchable, electrochromic films can be deposited on polymers at high speeds by plasma enhanced chemical vapor deposition (PECVD) in a process that may be suitable for roll coating. This paper describes the electrochromic coatings and the PECVD processes, and speculates about their adaptability to high-speed roll coating.

## ELECTROCHROMIC FILMS

Electrochromic films are multilayer stacks that behave like batteries with visible indication of their state of electrical charge [1, 2]. They are opaque when fully charged, partially transparent when partially discharged, and fully transparent when fully discharged.

Figure 1 shows schematic cross-sections through typical films. Two transparent conductor layers sandwich the three active layers. In the middle is the ionic conductor, which serves as an electrolyte that conducts the mobile ions from the storage (counter electrode) layer to the electrochromic layer when the film is switched from transparent to opaque. The electrolyte layer may be a polymeric

A. Solid state coating

B. Laminated coating

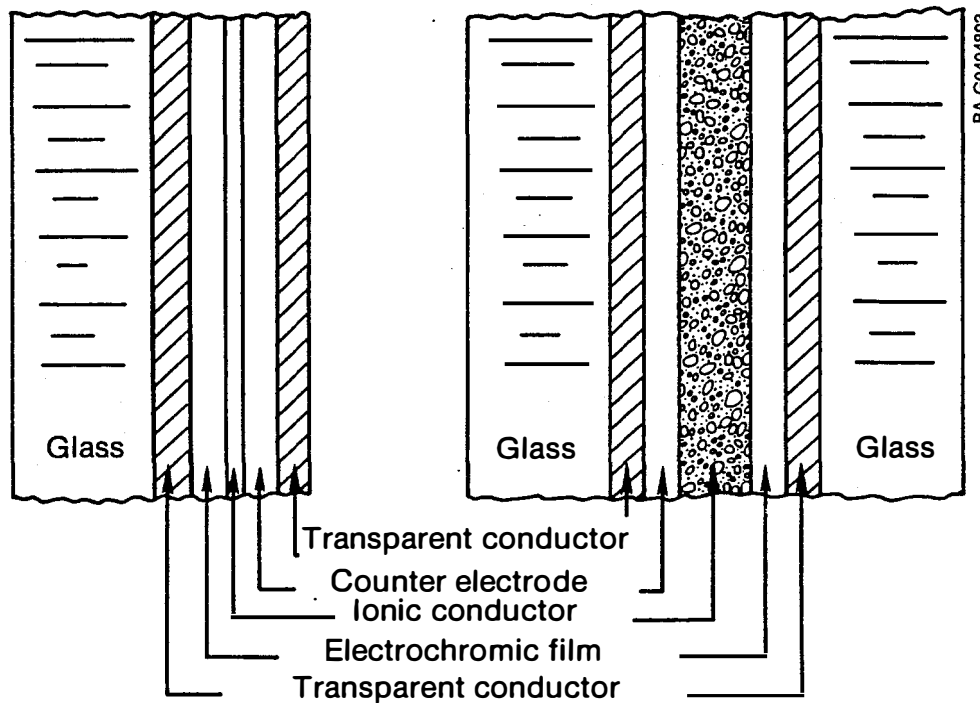


Fig. 1. Schematic cross-sections through typical electrochromic films

conductor or an inorganic, solid, ionic conductor such as lithium nitride or lithium niobate.

A wide variety of electrochromic materials and stack configurations have been studied. The most common is tungsten trioxide, which changes from transparent to dark blue when small ions such as hydrogen or lithium are inserted into its crystal lattice. Typical electrochemical reactions at the electrochromic layer are



where A is a metal such as tungsten, molybdenum, vanadium, iridium, or nickel; B is almost always oxygen;  $C^{m+}$  is a small ion (usually  $H^+$  or  $Li^+$ ); and  $x$  is the fraction of small ions per molecule of  $AB_n$  (usually much less than 1). A number ( $mx$ ) of electrons,  $e^-$ , must also be inserted into the electrochromic material along with the ions to maintain charge balance in the electrochemical reaction.

The two different materials,  $AB_n$  and  $C_x AB_n$ , have different optical properties: one is transparent and the other absorbs light in proportion to  $x$ . By electrochemically switching the electrochromic layer between these two compositions, the film is switched continuously between transparent and opaque or any partially absorbing state in between.

The electrochromic films must be relatively thick for two reasons. First, the electrochromic material absorbs light in proportion to the concentration  $x$  of ions inserted into it, but this concentration must be kept low enough to prevent irreversible changes from occurring in the lattice of the electrochromic layer. Consequently, the film must be thick enough to contain enough inserted ions in its thickness without exceeding the ion concentration limits of electrochemical reversibility.

The second reason that the electrochromic film is thick is the requirement for low-resistance, transparent, conductor layers. Otherwise, the electrochromic film would switch nonuniformly because of voltage drop across the face of the window. The effect would be like an opaque window frame slowly shrinking until the transparent center portion of the window finally disappeared. Sheet resistances well under 100 ohms per square are likely to be needed.

## "SMART WINDOWS"

The sunlight transmitted by a window may cause a significant burden on the air-conditioning system by bringing as much as 500 W of unwanted heat into the building per square meter of window. Electrochromic films can act as very efficient "valves" to control this solar heat gain. They are low-voltage devices (typically 3 V or less) requiring very little electrical energy to switch (typically less than 0.5 Wh/m<sup>2</sup>). By automatically controlling the electrochromic "valve" the benefits of view and daylighting can be retained while the burden of unwanted heat gain is reduced.

An optimal strategy for control of an electrochromic window would give top priority to daylighting. The occupant would switch on the lights as he or she enters a room and set the desired lighting level. The electrochromic film would automatically become more transparent until the desired lighting level was sensed by a light sensor in the work area. If insufficient daylight were available, the electrical lights would be adjusted automatically to provide the desired light. When the occupant left the room, he or she would turn off the lights, and the windows would automatically darken or lighten depending on whether the building was in a cooling or heating mode. A centralized building load management computer or a local area controller using indoor and outdoor temperature sensors would determine the current mode of the building's space-conditioning system.

This kind of strategic control over the amount of sunlight transmitted by a window has suggested that the term "smart window" be used for windows incorporating the electrochromic films. The concept is in keeping with the growing use of centralized computer control in buildings and the "smart house" design philosophy for residential buildings.

Analyses have indicated that an optimally controlled smart window in a commercial building would save about 70 kWh of heating and cooling energy per square meter of window each year in most parts of the United States [3]. The major reduction in electric power usage would occur during periods of peak demand, greatly reducing the 1600 MW of new peak power demand now created each year in the United States by newly installed commercial

windows. Visual glare and unwanted radiant heating near sunny windows would also be prevented, improving occupant comfort and productivity.

### PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION (PECVD) OF ELECTROCHROMIC FILMS

Large-area coatings are commonly made by thermal evaporation or sputter deposition. For very thin films, these coating processes are very fast and practical. However, the electrochromic films are

probably too thick for these deposition processes to be economical. Figure 2 compares the thickness of an electrochromic coating to a low-emissivity (low-e) coating and to an amorphous silicon photovoltaic cell. The electrochromic film is about 20 times thicker than the low-e coating and is more similar in complexity and thickness to the PV cell. This comparison suggests that the electrochromic film might be more economically made by the PECVD process used for the PV cell rather than by the much slower physical deposition processes used for the low-e and similar thin coatings.

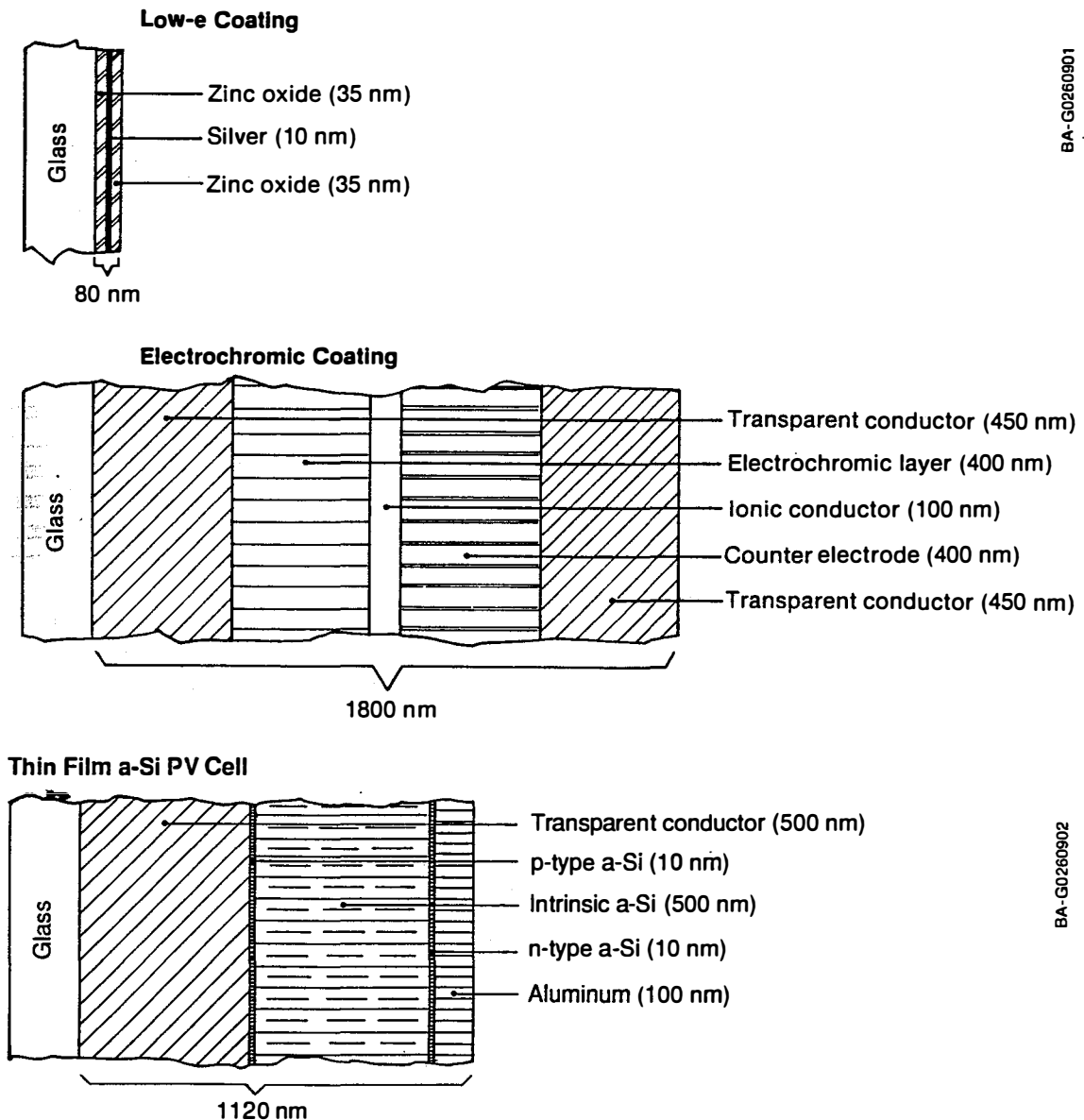


Fig. 2. Comparison of cross-sections through three typical large-area coatings (thicknesses to scale)

The PECVD process involves reacting gaseous materials at low pressure in a radio-frequency excited plasma. Typical reactions for production of electrochromic metal oxides are [4, 5]

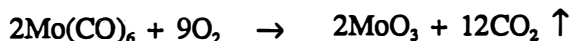
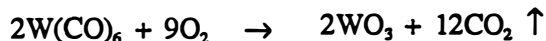
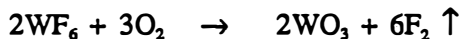


Figure 3 shows typical deposition rates for electrochromic tungsten oxide deposited from tungsten hexafluoride in an oxygen plasma. The deposition rate is quite high and limited only by reactant supply up to a deposition rate of about 40 nanometers per second (nm/s).

As the deposition rate increases, the density of the oxide deposit decreases. Decreased density in the metal oxide films is correlated with more rapid electrochromic responses; however, at very high deposition rates the deposit becomes powdery and incoherent. The maximum deposition rate for a useful tungsten oxide film is probably about 40 nm/s. This is about 10 times the rate possible with physical vapor deposition.

Apparently, the reactions in the low-pressure gas phase form multimolecular clusters in the oxide vapors. Consequently, the full latent heat of the oxide vaporization is not released as these vapors condense onto the substrates. The resulting heating of the substrate is minimal, and electrochromic oxides can be readily deposited onto temperature-sensitive polymer films.

The PECVD process is versatile enough to produce the other component layers in the electrochromic film stack as well. For example, high-quality, transparent, conductive oxides such as antimony-doped tin oxide have been made by room temperature PECVD using tetramethyl tin and antimony pentachloride in an oxygen plasma [6].

### ROLL COATING

It is interesting to speculate about the possibility of using the high-deposition-rate PECVD process for making the thick electrochromic films in a semicontinuous roll coater. It may be possible to use a five-chamber coater to deposit all five layers of the film in a single pass. If each layer could be deposited at the same 40 nm/s, then the entire 1800-nm-thick stack could be deposited in 45 s

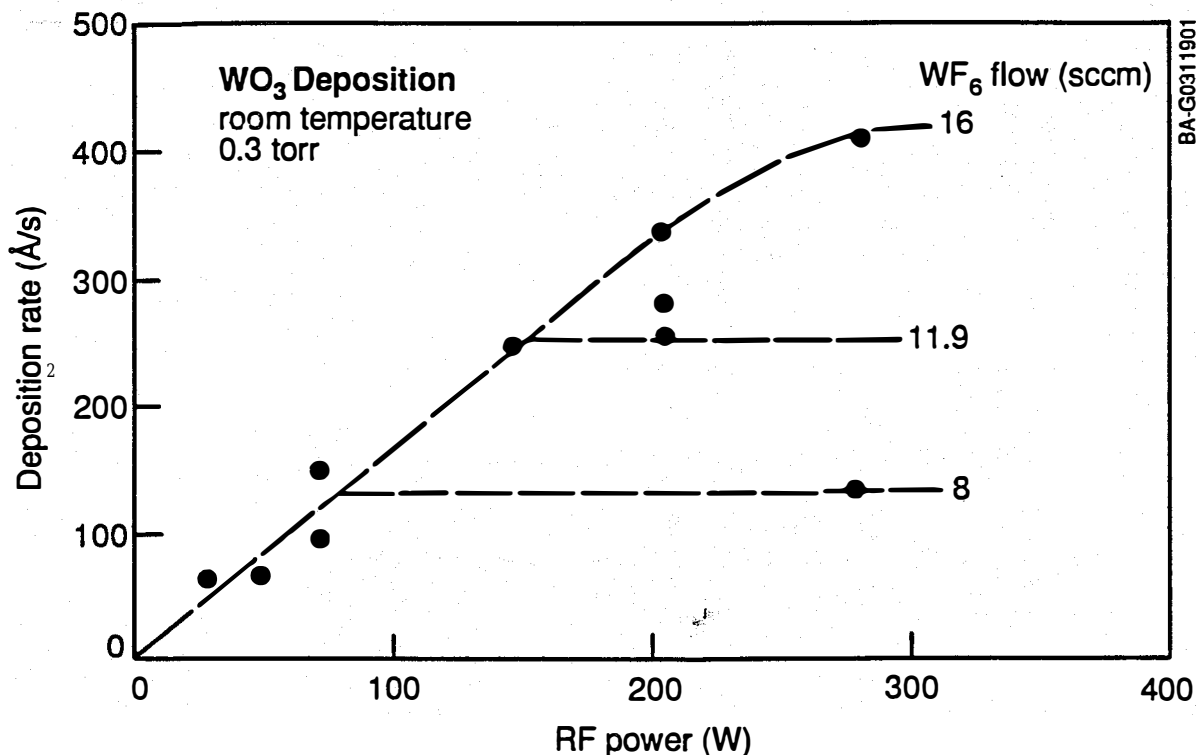


Fig. 3. Deposition rates for tungsten oxide films formed by PECVD at room temperature

using a 1-m-diameter drum rotating at 0.67 rpm. Although this production rate is slow compared to conventional roll coating standards, the economics of the process must also be considered.

It is likely that the electrochromic film would sell for more than \$50/m<sup>2</sup>. A 1-m-wide coater operating at 0.67 rpm (0.035 m/s) could produce more than one-half million square meters of electrochromic film worth more than \$25 million per year. Consequently, the value of the product should more than compensate for its relatively slow production rate.

#### TECHNICAL BARRIERS

Electrochromic films for window applications are not yet fully developed although research progress around the world is accelerating [1]. Several technical issues remain to be resolved before a practical and economical "smart window" film can be introduced into the buildings industry.

The films must combine functionality, aesthetic acceptability, durability, and cost-effectiveness. Functional electrochromic films have been developed, and some have acceptable aesthetics (are not too colorful when they switch). The use of PECVD has the potential of making the films economically. However, the present state-of-the-art films still lack the necessary durability. They appear to suffer from a number of degradation processes [7], including ultraviolet (UV) light degradation by an as-yet-unknown mechanism [8].

When the durability problem is solved, then more research will remain to develop suitable high-rate deposition processes for the other layers in the electrochromic film. The authors recommend exploration of the PECVD process for this purpose in anticipation of the solution to the UV durability problem.

#### CONCLUSIONS

Electrochromic "smart windows" may provide a way to improve the comfort in buildings while decreasing air-conditioning energy use and peak power demands. The thick, multilayer nature of electrochromic films requires that a high-deposition-rate process be used for their economic production. PECVD can be used to deposit electrochromic metal oxides and transparent conductive oxides at suitably high rates onto low-temperature substrates, making possible the fabrication of electrochromic coatings on polymer films for new windows and for retrofit applications to existing

windows. With about 60 million square meters per year of new windows and about 2 billion square meters of existing windows in the United States, the market potential for "smart" electrochromic window films is very large. However, many technical issues remain to be addressed before electrochromic films can be made economically.

#### ACKNOWLEDGEMENTS

The authors gratefully acknowledge A. Johncock-Krisco (now at Ford Glass Co.) and J.S.E.M. Svensson (now at COAT in Sweden) for their research assistance while at SERI. This work was supported by the U.S. Department of Energy's Solar Buildings Program under contract No. DE-AC02-83CH10093.

#### REFERENCES

1. C.M. Lampert and C.G. Granqvist (editors), Large-Area Chromogenics: Materials and Devices for Transmittance Control, SPIE Optical Engineering Press, Vol. IS 4, Bellingham, WA, USA, 1990.
2. M.K. Carpenter and D.A. Corrigan (editors), Electrochromic Materials, Proceedings, Vol. 90-2, The Electrochromic Society, Pennington, NJ, USA, 1990.
3. W.A. Bartovics, The Thermal Performance of Fixed and Variable Selective Transmitters in Commercial Architecture, Institute of Technology, Cambridge, MA, USA, 1984.
4. C.E. Tracy and D.K. Benson, J. Vacuum Science and Technology, Vol. 4, p. 2377, 1986.
5. C.E. Tracy, D.K. Benson and M.R. Ruth, U.S. Patent #4,687,560 (Aug. 18, 1987).
6. A.R. Lefkow and J.C. Lee, Selective IR Reflection Coatings Development, Report, DOE Contract No. DEAC04-78CS34299, Oct. 1979.
7. A.W. Czanderna and C.M. Lampert, Evaluation Criteria and Test Methods for Electrochromic Windows, SERI/PR-255-3537, in press, 1990.
8. M. Mizuhashi, J. Nagai and T. Kamimori, in Large Area Chromogenics: Materials and Devices for Transmittance Control, op. cit. pp. 494-503.