

Solid-State Monolithic Electrochromic Switchable Visors and Spectacles

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ABSTRACT

There is a need for variable transmission technology for Goggles, Spectacles, and visors for Helmet-Mounted Displays (HMDs). At present, most HMD's do not allow the pilot to control the transmission level of a flight visor while transitioning from high to low light levels throughout flight. Sunglasses are often used for non-HMD conditions but become impractical for HMD use. For individuals moving from high to low brightness levels, momentary blindness is an issue in both recreational sports and military applications. A user-controlled or automatically controllable variable-transmittance lens is a possible solution. The Eclipse Visible Electrochromic Device (EclipseECD™) is well suited for these light modulation applications. The EclipseECD™ modulates light intensity by changing the absorption level under an applied electric field. The optical density may be continuously changed by varying voltage allowing for analog instead of digital (on/off) light levels. EclipseECD™ is comprised of vacuum deposited layers of a transparent bottom electrode, an active element, and a transparent top electrode, incorporating an all, solid-state electrolyte. The solid-state electrolyte eliminates possible complications associated with gel-based or liquid crystal based technologies including lamination, and precludes the need for additional visor modifications. This all solid-state ECD system can be deposited on flexible substrates, eg. PET, PC, etc. The low-temperature deposition process enables direct application to polymer lenses and HMD flight visors. Additionally, the coating is easily manufactured; can be trimmed, has near spectral neutrality and fails in the clear (bleached) condition.

Keywords: spectacles, helmet-mounted display, variable-transmittance visor, electrochromic device, thin films

1.0 INTRODUCTION

Presently, there is a wide array of applications spanning multiple industries that can and do benefit from switchable devices exhibiting a reversible optical change when viewed in transmissive or reflective modes. Devices operating in the mid- and long- wavelength infrared spectrum (MWIR & LWIR) have applications as sensors and tunable filters¹, as well as variable emissivity components on thermal control systems for terrestrial and space applications. Large-area devices that modulate light in the visible spectrum have been explored in automotive and architectural applications such as smart windows/mirrors² and skylights, while smaller-sized devices have generated considerable interest for dimmable eyewear applications for military, law enforcement, and civilian markets. The present work is directed to the use of electrochromic variable transmittance devices in these markets.

More specifically the Eclipse Visible Electrochromic Device (EclipseECD™) is applicable to helmet mounted displays and spectacles. In very bright conditions a pilot or warfighter can usually soothe eye-strain with a tinted sun-visor or sunglasses. With helmet-mounted displays integrated into the helmet/visor unit, the use of an extra sun-visor or sunglasses may not be practical. Similarly, in combat situations and in most recreational activities, removal of eyewear due to light conditions can be problematic. To adapt to various light intensities, a pilot/warfighter will experience during a mission, one attractive option is to vary the transmission of the visor or spectacle itself, and hence adapt to the situation at hand. Furthermore, for comfort, the transmission through the visor should be continuously adjustable throughout the possible illumination levels a pilot experiences during a mission.

This paper will focus on these eyewear applications of electrochromic devices. Eyewear requirements and the performance of Eclipse devices are evaluated.

2.0 BACKGROUND

The status of helmet mounted displays (HMDs) has been recently reviewed^{3,4}. The most frequently selected sources for helmet-mounted displays include cathode ray tubes, active-matrix Liquid-Crystal displays (AM-LCDs), organic light emitting diodes (OLEDs), liquid crystal on silicon (LCOS), ferroelectric liquid crystal on silicon (FLCOS), time multiplexed optical shutter (TMOS) and electroluminescent (EL) systems. Suspended particle approaches and electrochromic systems are also being considered for this application. The configurations for head mounted displays have been defined by KELLER *et al.*⁵ as follows:

- 1) *monocular*—both monochromatic, early designs and later full-color versions;
- 2) *opaque HMD*—displays imagery to the wearer while occluding the real world;
- 3) *optical see-through*—displays high contrast monochrome or full color imagery, superimposed (ghost like) over the real world;
- 4) *video see-through*—displays computer generated imagery that can fully occlude real world imagery; real and virtual images are available as a single digital composite.
- 5) *projection HMD*—projects superimposed imagery or cues directly on top of real world surfaces or on retroreflective surfaces for training use;
- 6) *selective occlusion*—merges qualities of optical and video see-through.

Each of these configurations has advantages and disadvantages when employed in defense applications. In many situations, the optical see-through and video see-through configurations are best as a result of requirements to be able to involve the wearer in decisions based on visual cues from the real-world environment. If the background is too complex or too bright, the optical see-through approach suffers reduced effectiveness in reading the display. This problem can be addressed by altering the layout of the display depending on the characteristics of the environment⁶. The display may be presented to one eye (monocular mode) or to both eyes (biocular or binocular mode). In the biocular mode, the same video channel is presented to both eyes. The benefits of the approach are improved comfort and enhanced detection of objects in the field of view. The binocular mode presents images or video such that each eye views the output of a different sensor. This can lead to additional design criteria necessary to reduce the operational and performance costs of binocular rivalry, described as processing the image from eye or the other but not both. The same situation can occur in a semitransparent monocular helmet mounted display where one eye views the far scene and the other eyes views the display and the far scene. Binocular rivalry is affected by the relative contrast of the images. The characteristics of representative helmet mounted displays are given in Table I⁷.

Table I. Display Source Characteristics

	CRT	[AMLCD]	FLCOS	OLED	TMOS
Diagonal Size (inch)	> 0.5	> 0.7	> 0.6	> 0.66	> 0.5
Life Span (Hours)	40,000	20,000 - 40,000	10,000 - 15,000	<10,000	>100,000
Brightness (cd/m ² or Nit)	~100	<100	300 - 1000	100 - 700	200 - 1000
Contrast ratio	300:1 - 700:1	150:1 - 450:1	Up to 2000:1	150:1 - 450:1	300:1 - 4500:1
Type of Illumination	Raster Scan	Backlight Illumination	Illumination Optics	Self Emissive	Time Multiplex Optical Shutter
Pixel Response Time	Phosphor Dependent <1sec	1-30ms*	1-100us	<1ms	0.1 - 100μs
Colors	16.7M	16.7M	16.7M	16.7M	16.7M

* sub-ms may be obtained using dual-frequency materials

From [7]

Alternatives to liquid crystal-based displays have been sought to overcome requirements for polarizers, inherent distortion and the presence of liquid phase components. Polymer electrochromics have been evaluated as a component in heads up displays⁸. The electrochromic can be used to dim the luminance from the scene, thereby allowing improved visibility for the display. This “dark visor” mode of operation can improve the contrast under high ambient light conditions. The extreme of “dark visor” operation embodied in an “eyes out” design involves presenting both the external scene and the display via a protected channel to reduce or eliminate danger from external threat conditions. Initial findings indicated that polymer electrochromic displays could meet design specifications of low power consumption, wide transmission range, fast switching speeds and long lifetime. All solid state inorganic electrochromic displays have also been previously reported⁹. The system was based on an electrochromic stack consisting of indium tin oxide/a-WO₃/MgF₂/Gold. It was found that amorphous tungsten oxide having oxygen vacancies and hydrogen ion transport provided an optical density of 3.5. Nanostructured antimony-doped tin oxide electrochromic materials have been used on Mylar substrates to prepare a printable display having rapid response and a contrast ratio as high as 7.0¹⁰.

Most of the considerations for helmet mounted displays also apply to head-mounted displays, variable transmittance sunglasses and spectacles. These components also require variable transmittance to adjust for both high-glare and low-light scene conditions. “Eyes out” operation can be incorporated in each of these devices as long as image sensing and transfer is made available. This work is concentrated on the light level control of HMD units by combining it with and ECD.

3.0 ELECTROCHROMIC DEVICE TECHNOLOGIES

Electrochromic Devices (EclipseECD™) have the property of being able to continuously change transmission by applying a small potential¹¹. This is a reversible process tailorable to a range and speed for convenient adjustment of the light level to an arbitrary setting within the ECD’s range (analog as opposed to digital control), (i.e., it not only has an on/off type of maximum/minimum transmission setting, it could have a manual and /or sensor-assisted adjustment of comfort level of transmission).

ECDs most prominent application to date is in anti-dazzling rear-view mirrors for automotive applications. This is a common accessory to cars today. Other automotive applications like ECD sunroofs are emerging at this time. The ECD “Smart Window” for buildings has big implications on energy-savings, though this application relies on achieving large scale deposition technologies and competitive pricing. There are also applications for ECDs in the infrared (IR), for example control of the emissive properties of surfaces. This is of particular importance in space applications.

In an electrochromic material the optical properties of the material change during intercalation or deintercalation of ion electron pairs into the host material. It is clear that a material with different states of composition may have different optical properties, (i.e., can be more or less transparent). On the other hand, the physical processes behind the changes in the optical properties in electrochromic material are not well understood for all materials.

Example materials for Electrochromism are typically transition metal oxides^{12,13}. There are cathodic and anodic coloring materials, they change from transparent to colored state upon insertion of ions-electron pairs (cathodic) and upon extraction of ion-electron pairs (anodic). The cathodic reaction can be described in chemical terms as:



Where MO is a transition metal oxide and I⁺ and e⁻ are small low molecular weight ions and electrons respectively.

The coloration taking place in MO upon ion/electron-insertion can be modeled with the small polaron theory^{14,15,16}. The insertion of an ion into the MO film is accompanied by insertion of a charge-balancing electron. The electrons enter localized states below the conduction band and initiate a local polarization, thereby creating a self-induced potential well. The polaron only affects the nearest neighbors and hence is called a small polaron. The electron will change the valence-

state of its host metal site from M^{+X} to M^{+X-1} . The coloration of the MO, or rather the absorption of light, take place when the polaron absorbs light, get excited, and jumps to an adjacent metal site. Maximum coloration is achieved with an Ion to M ratio of about 0.1-1 for different electrochromic transition metal oxides. At this ratio there are several M^{+X} sites surrounding the M^{+X-1} small polaron site resulting in a high probability for the small polaron to absorb light and jump to the adjacent metal site.

4.0 THE ELECTROCHROMIC DEVICE

The ECD works in a way similar to rechargeable batteries; ions are transported from one electrode to the other, and reversibly back again. The major difference between a rechargeable battery and an ECD is that the latter is transparent. There are two major groups of electrochromic materials, organic materials, where Prussian Blue is one of the most studied (Figure 1), and inorganic materials like transition metal oxides (Figure 2).

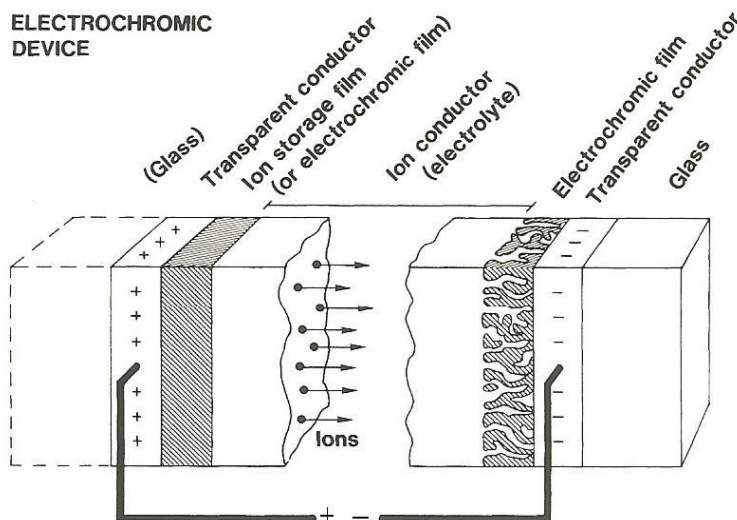


Figure 1. Basic schematic of a laminated electrochromic device, indicating transport of positive ions through a polymer electrolyte under the action of an electric field¹⁷

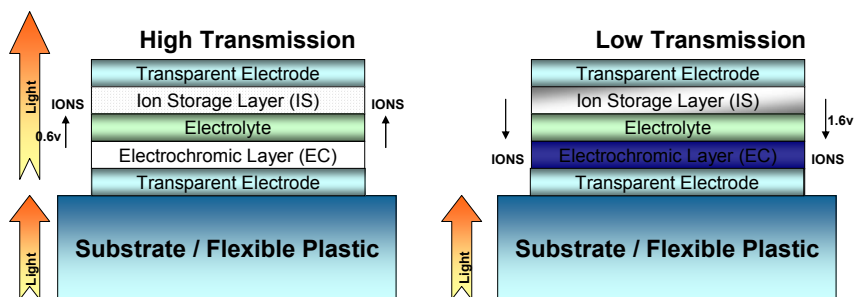


Figure 2. Basic schematic of an inorganic all solid state and monolithic electrochromic device. Ion movement through an inorganic electrolyte is indicated by arrows in the figure.

A transparent ECD will contain a number of layers with different properties. First a substrate, glass or plastic, with a transparent conducting layer. On top of the transparent conductor is the electrochromic layer, followed by an electrolyte and a counter electrode and a top electrode. These three layers electrochemically function in a similar to a battery. The counter electrode can be either an optically passive ion-storage layer, or an active electrochromic layer. In the latter case a cathodic and an anodic coloring material are matched to each other. Complementary layers like this will increase the coloring efficiency of the device as the cathodic layer colors upon ion insertion and the anodic layer colors upon extraction of ions.

On top of these layers a final conductive layer is deposited. In a reflective ECD one of the conductive films can be exchanged to a highly reflecting metal. In Figures 1 and 2 complete devices are depicted. Transport of ions is also indicated in the figures.

There are two major approaches to the electrolyte in ECDs (Figure 3). The first is a polymer electrolyte, where the anode and cathode are deposited on two separate substrates and subsequently laminated together with binder functioning polymer electrolyte¹⁴. Secondly, there are all-solid-state monolithic devices. In this type of device all layers may be vacuum deposited on a single substrate.

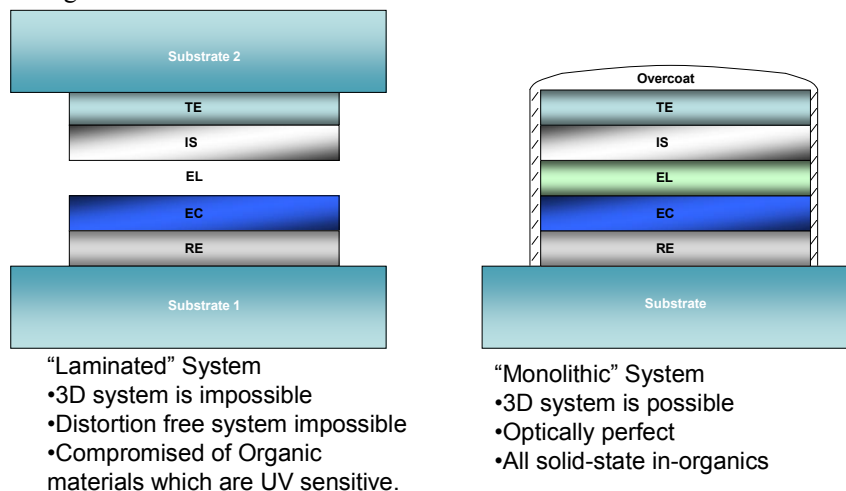


Figure 3. Simple schematic of the differences between laminated polymer electrolyte and an inorganic all solid state monolithic electrochromic devices.

Both approaches have their advantages and disadvantages. The polymer device is relatively easy to manufacture but polymers are not completely stable to UV radiation. The all-solid-state monolithic device is more difficult to manufacture. This type of ECD is not sensitive to UV radiation. An all-solid-state EclipseECD™ is deposited on one substrate with a good process control of composition and avoids contamination of interphases between subsequent layers.

The all-solid-state monolithic devices have the advantage to be applicable on curved surfaces. Furthermore, it is possible to deposit on top of other coatings and hence the dimming effect of an EclipseECD™ is separated from, and does not interfere with the display-function of an HMD.

5.0 APPLICATIONS

Eclipse Energy Systems, Inc. employs both inorganic and organic materials, as well as all-solid-state, monolithic and laminated devices. Furthermore, Eclipse Energy Systems has a long history making ECDs and a unique knowledge of electrochromic materials and systems.

The technology requires curved substrate application for successful integration into most complex curve eyewear. The technology has recently been placed onto small, complex curved surfaces (Figure 4) and is planned to be scaled up to visors.



Figure 4. Representative evolution of devices from flat substrates to small curved substrates, to large curved substrates.

An ECD for helmet mounted displays (HMDs) should be able to combine the day and night-visor into one single unit. This visor would require a wider transmission range than the sports visor described above, specifically, a higher transmission in the clear state. This will enable pilots to use the same visor for both night and day missions. To fulfill this goal a prescription-type visor with a transmission range from 80% to 18%, switching in a few seconds is required. This system will also be applicable for night vision goggles providing daytime functions (Figure 5).

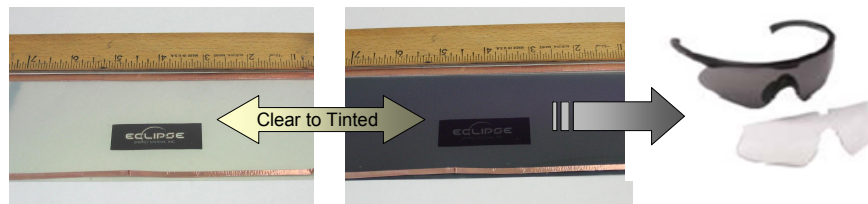


Figure 5. Example of device switched from bleached to dark condition (80% to 18% transmission).

Eclipse has tailored such an electrochromic system to show that an ECD can meet these requirements. Figure 6 shows ECD-devices with a transmission range from 80% to 15%.

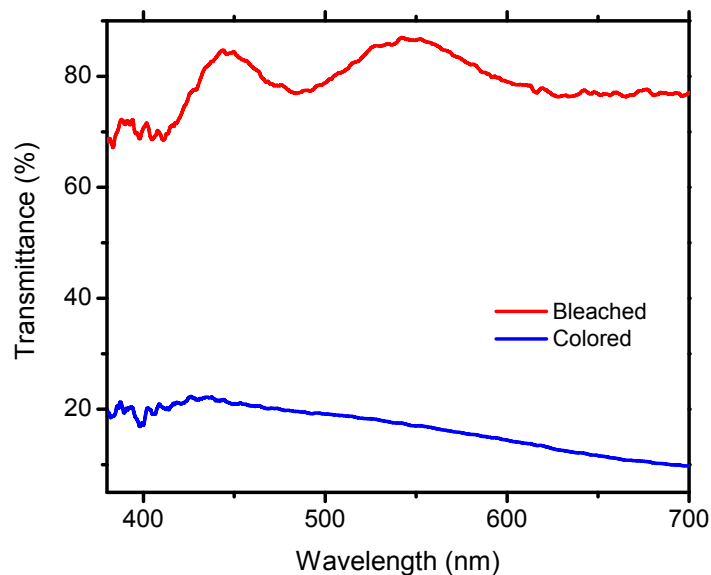


Figure 6. EclipseECD™ with transmission range from 80% to 15%

6.0 DISCUSSION

The challenge for the ECD used for HMD switchable visors is high transmission (around 86%) and short switching times (~1 sec). To meet the requirements for HMD Eclipse has employed an ECD system suitable for this application, and tailored it to meet the requirements.

The maximum value for the transmission is not only dictated by the active layers but also by the transparent conductor. The best transparent conductor, indium tin oxide (ITO), is deposited on glass and heat-treated to a crystalline state, where it exhibits excellent optical transmission and electrical conductivity. Heat-treatment is not possible on plastic and hence other solutions to improve the electrical conductivity are necessary. This implies that ITO on plastic-substrate in itself has a slightly reduced transmission compared to the best ITO deposited on glass. Eclipse has shown that an ECD is a viable option for HMD. The required range and speed has been demonstrated, and with some more tailoring to the application should result in an HMD-ECD that significantly improves on the environment in which a pilot is working.

7.0 CONCLUSION

The challenge of making an HMD-ECD combination system creates many new issues to overcome. These include curve surface deposition, PC vs. inorganic ECD layer miss-matching, ~90% to 12% optical performance requirements and high color and bleaching speeds. Eclipse's all-solid-state ECD can overcome all of these issues and currently has an 86% to 18% modulation, neutral coloration and switches within a few seconds.

8.0 REFERENCES

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