

Electrochromic Thermal Manager for Mini, Micro and Nano Satellites

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ABSTRACT

The thermal environments of satellites, in general, and futuristic mini, micro, nano and pico satellites, in particular, are in a constant state of flux. Each satellite houses valuable equipment having specified temperature limits and a range of heat generation rates. In order to maintain all equipment within operational temperature in this continuously temperature changing environment, an active thermal control system is required. Weight, size and energy requirements of the thermal controller of a satellite are a major challenge especially in light of the trend toward diminishing satellite size. In this paper, we present an active thermal manager capable of controlling the thermal conditions within a satellite and maintain a near room-temperature environment. The thermal manager is an electrochromic device (ECD) that changes the reflectance/emittance properties of the attached surface in a controllable manner.

I. INTRODUCTION

NASA has Nanosatellite based Astrobiology and Fundamental Space Biology Missions, in which the ECD technology would greatly enhance and extend the thermal control capabilities of the satellites and provide for more complex science missions.

Electrochromic (EC) materials are typically multi-valent transition metal oxides exhibiting different optical characteristics corresponding to their various oxidation states. Anodic EC materials are absorbing in their reduced states I_xEC , where I_x represents ion-electron pairs and x is the fraction of I attached to EC molecules. Conversely, cathodic EC materials (IS, referring to their ion storage function) are absorbing in their higher oxidation states, and less absorbing or non-absorbing in their reduced states I_xIS . To make an ECD operating with complimentary color changing components, we need both EC and IS layers, one of which is ion intercalated, and between them an electrolyte layer, EL, to enable ion transfer. The ECD system is completed by additional two electrodes contacting opposing sides of the optically active layers, to drive ions into the active layers and inject electrons into the system (Figure 1). The driving voltage of an ECD is typically around $\pm 1V$.

Electrochromic Device Structure, Materials, and Operation

The typical electrochromic device is comprised of a five-layer structure consisting of top and bottom electrodes, active electrochromic (EC) and ion storage (IS) layers, and an electrolytic medium (EL). Figure 1 illustrates two variants of this structure: Laminated vs. Monolithic. In a laminated system, two halves of the device are deposited on independent substrates, which then form a sandwich structure on either side of a liquid or semi-liquid electrolyte. In a monolithic system, the entire stack is deposited on a single substrate, often including a protective overcoat over the entire system.

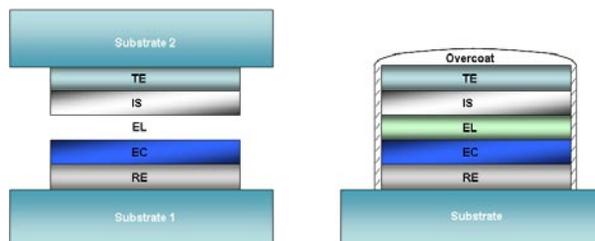


Figure 1. Variations of the typical five-layer ECD structure: Laminated vs. Monolithic

Monolithic systems provide many advantages to laminated systems. Laminated systems are typically comprised of organic materials which impart UV

sensitivity to the device, are hydrogen based, leading to charge leakage, and the presence of two substrates and a liquid or semi-liquid electrolyte make them relatively heavy. Also, the laminated structure produces optical distortion that is undesirable in visible applications. Conversely, inorganic monolithic thin film systems offer UV resistance, light weight, optical clarity, and relative stability due to the Li-based electrolyte.

The complimentary optical response of the electrochromic active layers via electrochemical reactions is illustrated in Figure 2 below. When an electric field is applied to the device, charge transport occurs across the electrolyte in the form of mobile ions (e.g. Li^+). The resulting intercalation (or de-intercalation) of ions into (or from) the EC and IS layers of the ECD produces complimentary changes in optical absorption within the layers, due to the change in oxidation state of the materials. This causes the device to switch between low absorption (bleached) and high absorption (colored) states. Changing the polarity of the applied field reverses the flow of ionic charge, and the system reverts to its previous state.

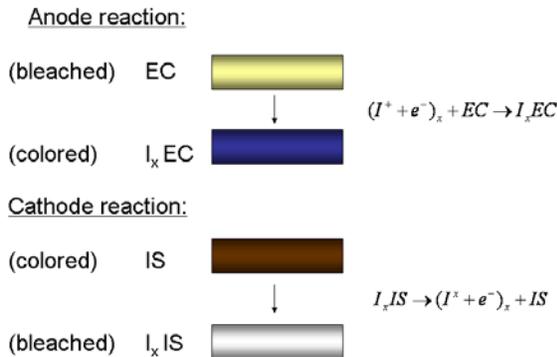


Figure 2. Complimentary electrochemical reactions occurring in the electrochromic (EC) and ion storage (IS) layers of an ECD are responsible for the optical switching effect.

Within the typical five-layer ECD structure, one or both of the electrodes may be transparent to the operating wavelength, depending on whether the device is to be used in a transmissive or reflective state. The Eclipse Vis-ECD is an example of a transmissive device¹, while the Eclipse IR-ECD² operates in a reflective mode, as shown below in Figure 3.

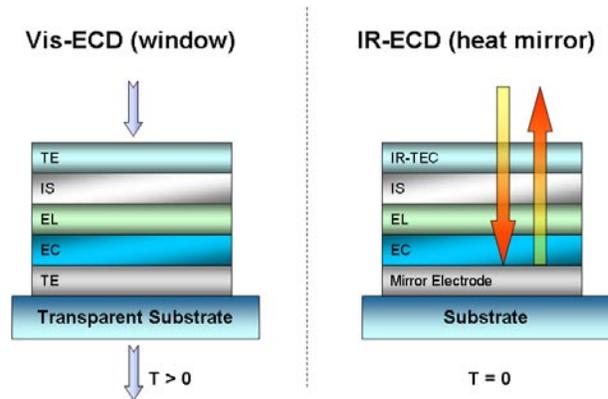


Figure 3. Eclipse visible (a) and infrared (b) electrochromic devices, operating in transmissive and reflective modes, respectively.

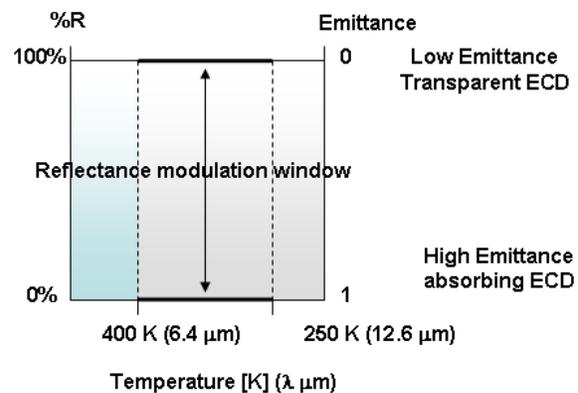


Figure 4. Reflectance-Emittance modulation of an IR-ECD in thermal (spectral) window. Since ECD is reflective, Absorption = Emittance = 1-Reflectance

II. ECLIPSE IR-ECD

Device Description

The Eclipse IR-ECD is Li-based, all inorganic, solid-state, monolithic system that may be deposited on rigid substrates (glass or polished thin metal surface) or on space-qualified flexible substrates (e.g. Kapton). Within its classical five-layer structure, the electrochromic (EC) and ion-storage (IS) films are the active layers of the system that color and bleach simultaneously. The electrolyte (EL) is the solid fast ion conductor, and EC/EL/IS is the active element sandwiched between two electrodes. The total thickness of the stack is less than $1\mu\text{m}$, resulting in an extremely light-weight system ($\sim 5\text{g}/\text{m}^2$). The IR electrochromic system is a switchable mirror working over the entire infrared region. One of the electrodes is an IR transparent electrode (TE), and the other is a reflective electrode (RE). The IR transparent electrode,

Meta-TEC™, is a unique metamaterial³, exhibiting 85-95% transparency for IR wavelengths from roughly 2μm to 26μm, while maintaining a metal-like conductivity (~2x10⁵ S/cm).

In the non-absorbing mode, light passes through the metamaterial top electrode and active element, and is reflected back from the mirror electrode. When the system is activated to its absorbing mode by the application of a low voltage (± 1V) to the electrodes, the reflected light intensity diminishes and the system goes into a low-reflectance, high-emittance (High-e) state. Reversing the electrode polarity brings the system back to a high-reflectance and low-emittance (Low-e) state. It has “emittance memory”, the ability to hold its emittance state, in High-e, Low-e, and intermediate states by merely disconnecting from the power supply. The Eclipse IR-ECD is a smart electrochromic system working as a heat modulator⁴.

III. RESULTS AND DISCUSSION

Device Performance

Figure 5 shows the emittance spectra of a typical IR-ECD corresponding to the colored (High-e) and bleached (Low-e) states, while Figure 6 shows the reflectance spectra for two different devices designed for hot (350K) and cool (270K) conditions, in their High-e and Low-e states. There are two important features to consider when reviewing these spectral results:

- 1) The system shows emissivity modulation over the entire IR region, dominating in the mid-wave IR (MWIR, 3-5μm) and long-wave IR (LWIR, 8-12μm)
- 2) The system shows reversible tuning properties in MWIR and LWIR regions.

The modulation properties of IR-ECD are related to the insertion/extraction- dependent development of molecular vibration absorption bands of the active materials. The tuning properties of the absorption bands upon intercalation or extraction exhibit red shifts in both the MWIR and LWIR regions. These red shifts are related to cooling properties of the sample. The wavelength-temperature relation given by Wien’s Displacement Law⁵ and presented as Equation 1, helps to calculate the ΔT (K) corresponding to the Δλ_{MWIR} and Δλ_{LWIR} regions in Figure 5.

$$\lambda (\mu\text{m}) = \frac{2898}{T (\text{K})} \tag{1}$$

If we apply this equation to both the MWIR and LWIR wavelength shifts in the IR-ECD spectra, we find that the sample cools down ~230K upon switching from Low-e to High-e states. This surface cooling accounts for the tuning properties of IR-ECD.

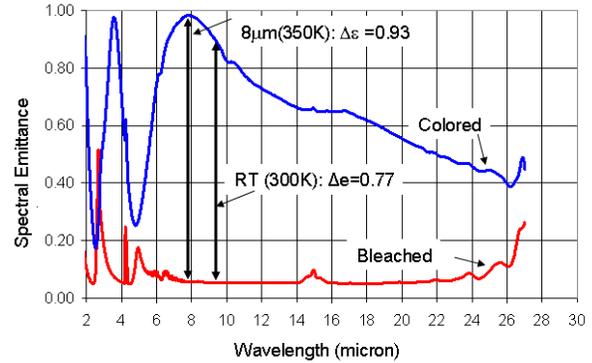


Figure 5. Emittance spectra of a typical Eclipse IR-ECD in High-e and Low-e states.

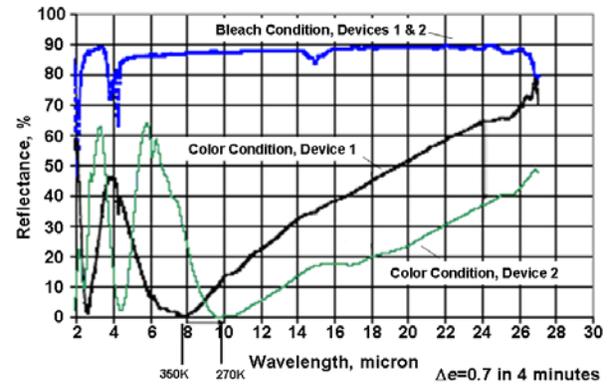
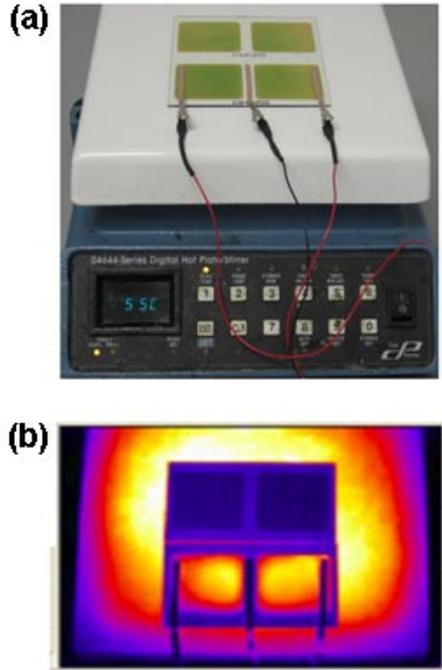


Figure 6. Reflectance spectra of two different Eclipse IR-ECD designed for hot (350K) and cool (270K) conditions.

Figure 7 shows optical and thermal images of IR-ECD devices heated to 55°C on a hotplate. Two of the samples are in Low-e states and the other two are at High-e states. Optical images show that the devices are nearly identical in appearance for both the colored and bleach states. To the thermal camera, the Low-e state devices appear much cooler than the hotplate temperature due to their effective heat retention, as indicated by their dark color in the figure. The High-e

state devices efficiently radiate heat, and thus appear to be at the same temperature as the underlying hotplate. Thus, thermal imagery clearly demonstrates that devices in the Low-e state retain heat, while those in the High-e state emit heat.



IR-ECD (x4) on 50°C hot plate
-- (Active Area 3.8cm x 3.8 cm each)
Low-e state (dark)
High-e state (yellow-red)

Figure 7. (a) Optical and (b) thermal imagery illustrating the efficient emissivity control of Eclipse IR-ECD heated on a 55°C hot plate.

The IR-ECD is a tileable and individually controllable technology capable of eliminating thermal gradients on satellite surfaces. It has the advantage of electronic controllability, low power consumption (~ 0.1 mW/cm²), light weight (~ 5 g/m²), and a high-to-low emittance ratio of $\Delta E \approx 0.90$ at $8\mu\text{m}$. Heating and cooling rates of IR-ECD devices have been tested in space^{6, 7}, and these tests show the functionality of the devices.

IV. CONCLUSIONS

The Eclipse Infrared Electrochromic Device (Eclipse IR-ECD) has the following capabilities:

- By providing individually addressable, variable emissivity tiles, the system is capable of

eliminating thermal gradients on small satellite surfaces. .

- The ability to actively modulate the emittance of each tile on the satellite surface extends the function of the skin of the satellite to serve as a thermal management radiator capable of handling different heat loads adjustable during space operations.
- A thermal management system including the Eclipse IR-ECD functions with low power consumption, minimal weight penalty and high variable emittance ratio.
- Allows complex tile geometries while retaining control of emittance modulation. Individual components can be cut or damaged and still function.
- Achieve dramatic weight savings by direct application of the Eclipse IR-ECD to the satellite outer surface.

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