# Effect of Active Area of a Complementary Electrochromic Device on Switching Response: Modeling and Simulation

Hwa-Chiang Lo,[a,b] and Kuo-Chuan Ho[b,c*]

[a]Material and Chemical Research Laboratories,
Industrial Technology Research Institute, Hsinchu, Taiwan

[b]Department of Chemical Engineering
[c] Institute of Polymer Science and Engineering,
National Taiwan University, Taipei, Taiwan 10617

## Abstract

The effect of active area of a complementary electrochromic device on switching response was investigated with computer simulation. The switching response curves of darkening and bleaching were simulated with an equivalent circuit model of a device. In this paper, a tungsten oxide/Prussian blue complementary device was used as our simulated system. The steady-state response of the charge density within a device was demonstrated. Computer simulation was performed by the finite element method software, as a COMSOL Multiphysics® program. According to our numerical results, we found out some useful information for the development and application of electrochromic devices. The dynamics of charge density showed the kinetic behaviour of charge transport. The log-log plot of injected or extracted charge density versus characteristic lengths for various different sizes showed an approximately straight line relationship. The semi-log plot of switching times versus characteristic lengths also showed an approximately straight line relationship. The larger active area needs the longer switching time. With changing the geometrical shape of active area and thermodynamic parameters in the two electrodes of electrochromic films, it is possible that the switching response can be analyzed and predicted. We will investigate parameter sensitivity for temperature with this model.

Keywords: Electrochromic device, Simulation, Active area, Switching Response

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*To whom correspondence should be addressed. Fax: + 886-2-2363-3040; E-mail: kcho@ms.cc.ntu.edu.tw

## 1. Introduction

Large-area electrochromic devices (ECDs) are better suited than liquid-crystal devices as light modulators, such as smart mirrors, smart windows, and space dividers.Because ECDs do not require use of polarizers, they allow a viewing angle approaching 180°. Moreover, control of their thickness is not important. The thin-film-type of ECDs has a low average power consumption (<2 V). Generally, the switching behavior of large area ECDs is one of the key performances. The switching response will become slower with the increasing active area of the device. Additionally, there is also the technical problem with any large area ECD. When the distribution of the current is uneven across the electrode surface, areas of patchy color may form because the electrical field can be larger at the edges of the electrode subtract nearest the metallic leads, if the electrode substrate is semiconductive like ITO. This allows an IR drop with distance towards the center of the active area. To improve the problem, it is necessary to understand the spatial profile and switching response of charge density, IR, and equilibrium potential in the device during the electrochromic process.

To the best of our knowledge, no one has reported the simulation of electrochromic process about the effect of active area on darkening time or bleaching time. In this paper, we want to apply this electrochromic model derived by Kase *et al.* and to perform the numerical simulations the switching response of the electrochromic process on two-dimension (2D) ECDs for various different sizes. The switching time may be predicted by simulating this model. Our numerical studies will be able to provide useful information about the charge density within the devices. Modeling the electrochromic process will allow the researchers to tune the device structure and to choose an active area that is optimized for a combination of darkening time and characteristic length. The model will also allow us to investigate the dependence of the darkening time on the electrolyte resistances and coloration conditions.

## 2. Model

A cross-sectional diagram of the ECD is given in Fig. 1a, where EC1 is the first electrochromic film, and EC2 is the second electrochromic film. A voltage applied across the transparent conducting oxide layer causes the reduction-oxidation reactions shown by the two electrochemical formulas as following

$$EC1 + xe^{-} + xM^{+} \leftrightarrow M_{x}EC1 \qquad [1]$$

(bleached) (darkened)

$$M_{x}EC2 \leftrightarrow xe^{-} + xM^{+} + EC2 \qquad [2]$$

(bleached) (darkened)

where $I_x$ is usually $Li^+$, e.g. from $LiClO_4$ electrolyte in propylene carbonate (PC), but it may also be $H^+$. The equilibrium potentials of the EC1 and EC2 are $E_{EC1}^{0}$ and $E_{EC2}^{0}$, respectively. In the development of the electrochromic model, we have used the assumptions that both the thickness and the non-faradaic charge of an ECD are regardless. To simulate the switching response, an equivalent circuit of the infinitely small area ECD for x-direction is considered in Fig. 2. According to the Ohm's law, the x-direction and y–direction current density, $I_x$ and $I_y$ are derived by

$$I_{x} = -(E_{x+\Delta x} - E_{x})/(2R_{sh,x}\,\Delta y) \qquad [3]$$

$$I_{y} = -(E_{y+\Delta y} - E_{y})/(2R_{sh,y}\,\Delta x) \qquad [4]$$

where $R_{sh,x}$ is the sheet resistance of the transparent electrode for the x-direction,

$R_{sh,y}$ is the sheet resistance of the transparent electrode for the y-direction, $E_x$ (or $E_y$) is the potential developed internally by structure for x-direction (or y-direction) within the device. According to material property, the sheet resistances are expressed as

$$R_{sh,x} = R_{sh}\,\Delta x/\Delta y \qquad [5]$$

$$R_{sh,y} = R_{sh}\,\Delta y/\Delta x \qquad [6]$$

where $R_{sh}$ is the sheet resistance of the ECD.

Equation differentiated twice with respect to x and y can be obtained as following.

$$\frac{\partial^2 E}{\partial x^2} = R_{ele}\frac{\partial^3 Q_{in}}{\partial t \partial x^2} + \frac{\partial \Delta E}{\partial Q_{in}}\frac{\partial^2 Q_{in}}{\partial x^2} + \frac{\partial^2 \Delta E}{\partial {Q_{in}}^2}\left(\frac{\partial Q_{in}}{\partial x}\right)^2 \qquad [7]$$

$$\frac{\partial^2 E}{\partial y^2} = R_{ele}\frac{\partial^3 Q_{in}}{\partial t \partial x^2} + \frac{\partial \Delta E}{\partial Q_{in}}\frac{\partial^2 Q_{in}}{\partial y^2} + \frac{\partial^2 \Delta E}{\partial {Q_{in}}^2}\left(\frac{\partial Q_{in}}{\partial y}\right)^2 \qquad [8]$$

According above equations, the governing equation can be derived as following.

$$\begin{aligned}\frac{\partial Q_{in}}{\partial t} &= \frac{R_{ele}}{2R_{sh}}\frac{\partial}{\partial t}\left(\frac{\partial^2 Q_{in}}{\partial x^2} + \frac{\partial^2 Q_{in}}{\partial y^2}\right) + \frac{1}{2R_{sh}}\frac{\partial \Delta E}{\partial Q_{in}}\left(\frac{\partial^2 Q_{in}}{\partial x^2} + \frac{\partial^2 Q_{in}}{\partial y^2}\right) \\ &+ \frac{1}{2R_{sh}}\frac{\partial^2 \Delta E}{\partial Q_{in}^2}\left[\left(\frac{\partial Q_{in}}{\partial x}\right)^2 + \left(\frac{\partial Q_{in}}{\partial y}\right)^2\right]\end{aligned} \qquad [9]$$

The initial conditions ($t = 0$) for an ECD are:

darkening process $Q_{in}(x, y, t = 0) = 0$

bleaching process $Q_{ex}(x, y, t = 0) = Q_0$

where $Q_0$ is the injected charge density corresponding to the minimum transmittance during the darkening process.

The boundary conditions ($t \geq 0$) on the bus bar are:

$$E_{app} = R_{ele}\frac{\partial Q_{in}}{\partial t} + \Delta E \qquad [10]$$

$$\text{darkening process} \qquad E_{app} = +1.2 \text{ V}$$

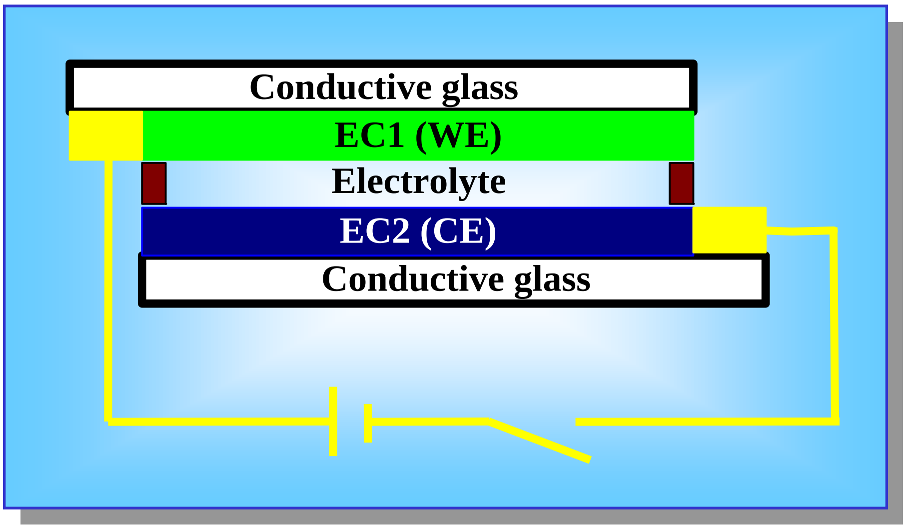
$$\text{bleaching process} \qquad E_{app} = -0.6 \text{ V}$$

where $E_{app}$ is the applied potential on the bus bar.

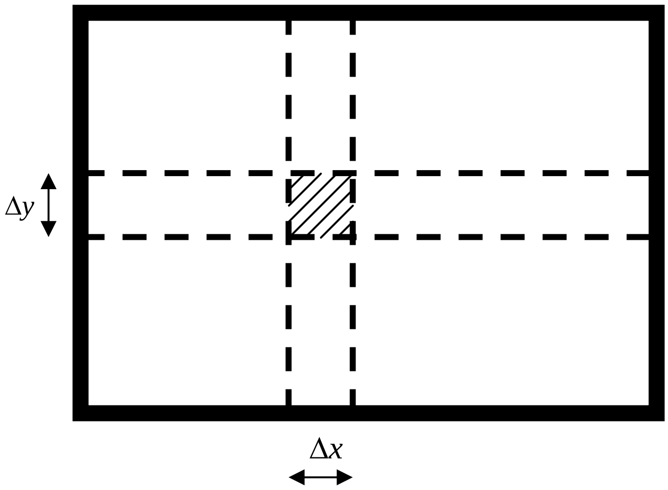
We perform the numerical simulations the switching response of the electrochromic process on 2D ECDs for four different sizes (size I: 4.8×5.4 $cm^2$, size II: 10.2×15.2 $cm^2$, size III: 16.0×41.5 $cm^2$, and size IV: 41.7×41.7 $cm^2$, respectively). The simulation parameters of the electrochromic model are given in Table 1. The transient problems defined above were solved by a program, which applies the finite element method. Computer simulation of each switching response takes 1-10 min on a PC equipped with a Pentium M 1.5 GHz processor and 1.25 GB memory and Windows XP Professional Edition operating system. The simulation results of the electrochromic model were summarized in Table 2.

## 3. conclusion

The switching response of a large area ECD can be interpreted by understanding the process of charge injection, the spatial profile of equilibrium potential and IR drop within the device. Based on these simulation results, we show that it is helpful to model an ECD for understanding the effect of active area on the switching time. In the future, according to simulate this model, we can design and analysis an ECD by combining structure and components for various requirements of specifications of active area and switching time. Also, we can evaluate effects of active area, substrate resistance, electrolyte resistance, and geometry shape etc. on the switching response of a large ECD. In the future, from point of view of commercial application, it is very important to understand the relationship between physical parameters and temperature.



[Fig. 1]



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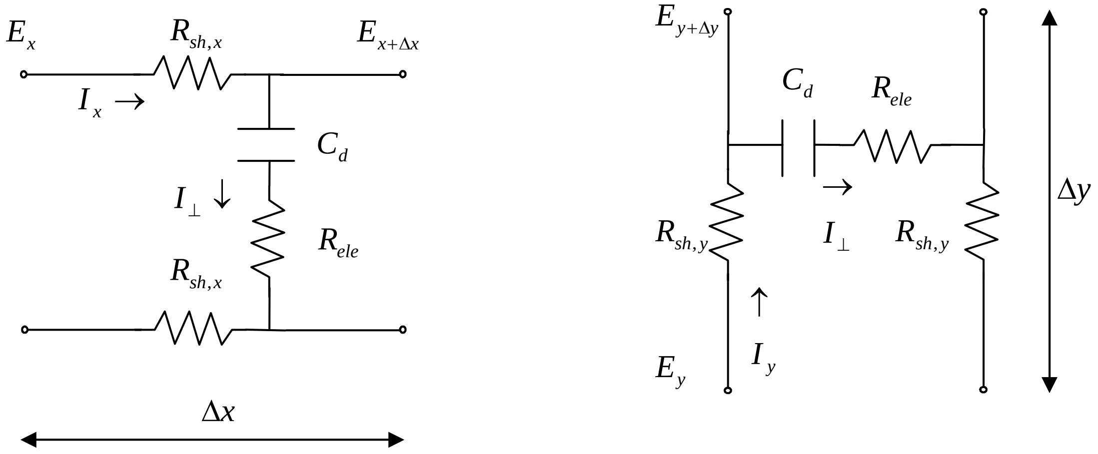
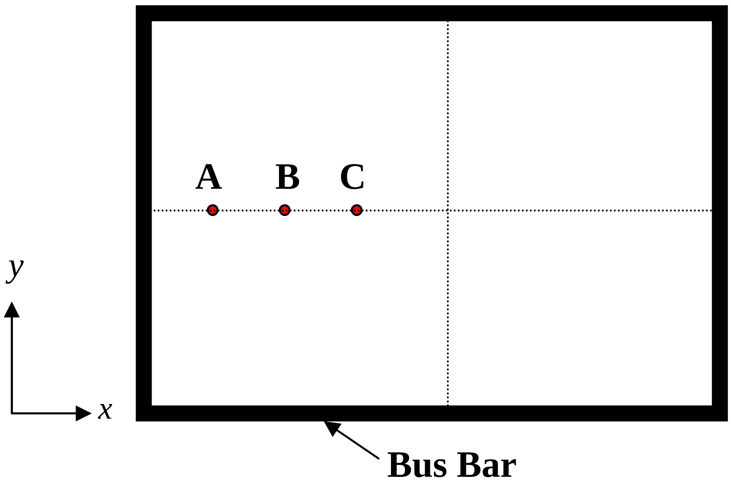
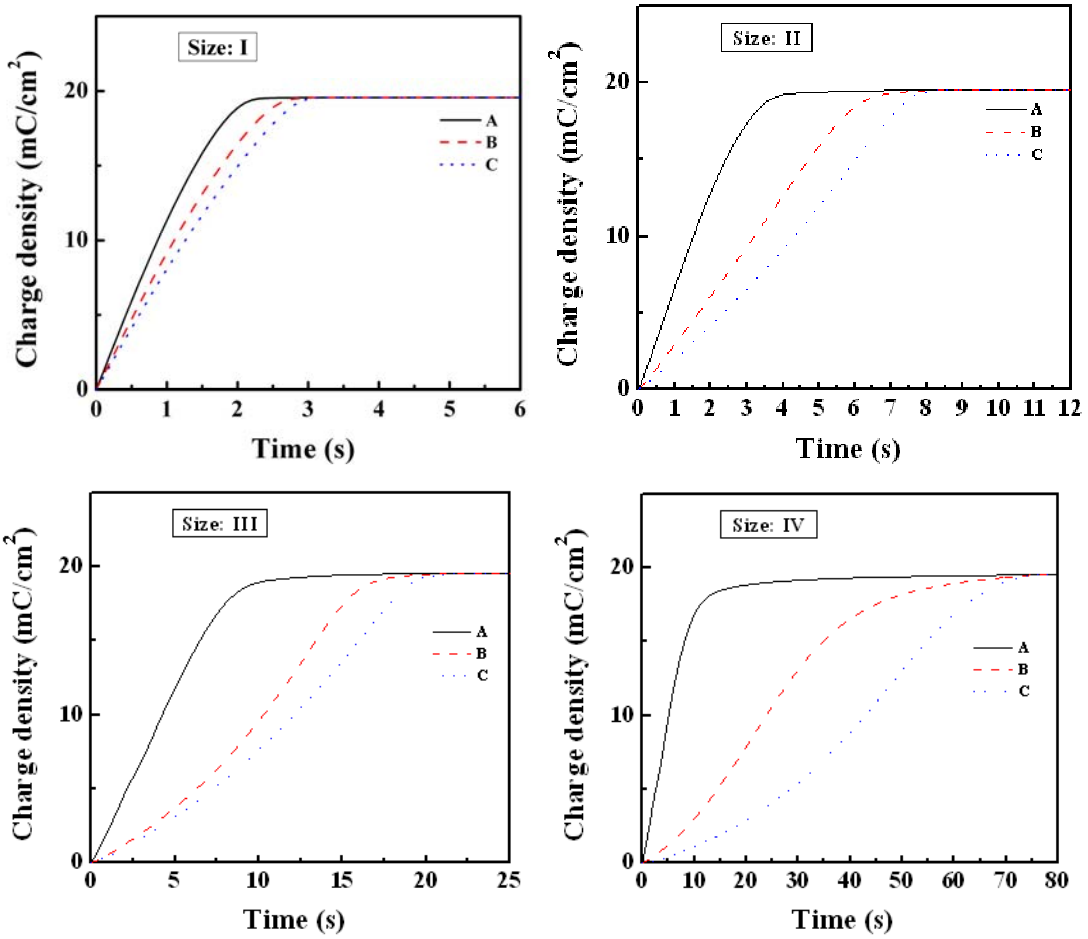


**[Fig. 2]**

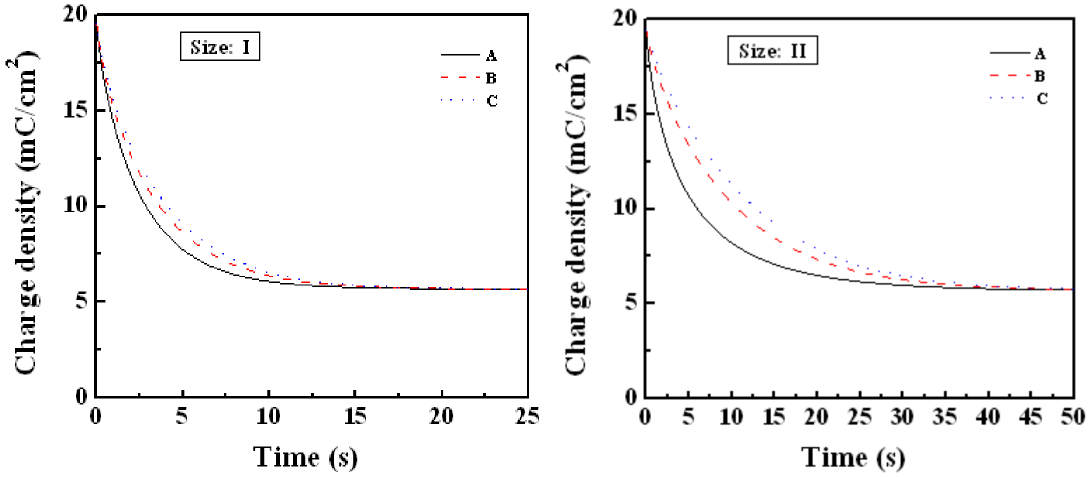


| Sample | Size (cm$^2$) |
|---|---|
| I | 4.8 × 5.4 |
| II | 10.2 × 15.2 |
| III | 16.0 × 41.5 |
| IV | 41.7 × 41.7 |

**[Fig. 3]**


Size: I
Size: II
Size: III
Size: IV
A
B
C
Charge density (mC/cm$^2$)
Time (s)
0
10
20
0
1
2
3
4
5
6
7
8
9
10
11
12
15
25
30
40
50
60
70
80

[Fig. 4 (a)]


Size: I
Size: II
A
B
C
Charge density (mC/cm$^2$)
Time (s)
0
5
10
15
20
25
30
35
40
45
50