ARTICLE IN PRESS

Solar Energy Materials and Solar Cells xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Electrochromic device with self-diffusing function for light adaptable displays

Seong M. Cho*, Tae-Youb Kim, Chil Seong Ah, Juhee Song, Sang Hoon Cheon, Hojun Ryu, Joo Yeon Kim, Yong-Hae Kim, Chi-Sun Hwang

Reality Device Research Division, ICT Materials & Components Research Laboratory, Electronics and Telecommunications Research Institute, 218 Gajeong-ro, Yuseong-gu, Daejeon 34129, South Korea

ARTICLE INFO

Keywords:
Electrochromism
Display
TiO_2 nanostructure
Light scattering

ABSTRACT

Light-adaptable (LA) displays combining the advantages of reflective and emissive displays, are considered as the future of display technology. Electrochromic devices are potentially strong candidates for reflective-mode LA displays because of their high transmittance in the transparent state and low power consumption. However, the narrow viewing angle of these displays in relation to a hybrid structure of the LA display, is a technical barrier that must be overcome for the successful application of electrochromic devices to light-adaptable displays. In the present study, an electrochromic device with a self-diffusing function was developed for application to light-adaptable displays. Si_3N_4 scattering particles were incorporated in the TiO_2 nanostructure-based electrochromic device. Efficient forward diffuse scatterings were obtained without deteriorating the total transmittance of the device. The contrast ratio and color gamut of the electrochromic device were dramatically improved because of the addition of the scattering particles.

1. Introduction

Nowadays, various kinds of displays are used in electronic devices. Based on the imaging method, these displays can be categorized into two groups: emissive and reflective displays. The emissive displays, such as organic light emitting devices (OLEDs) and liquid crystal displays (LCDs) with emissive backlights, produce images by self-emission of light. Although the image quality of this category of displays is excellent in indoor environments, their visibility becomes poor under very bright environments such as daylight, because of the surface reflection of the surrounding light. Reflective displays such as E-paper and electrochromic displays, on the other hand, produce images by reflecting surrounding light. These displays in general consume much less power than the emissive displays [1] with good visibility under daylight environments but very poor visibility in dark environments.

A display that can combine the advantages of these two categories of displays is thus desirable for future display technologies [2–5]. This kind of display is called a light-adaptable display [2,3]. In its simplest form, a light-adaptable display should consist of a hybrid structure of an emissive device such as a transparent OLED and a reflective device such as an electrochromic device, connected in tandem.

Electrochromic devices have been considered to be applicable to smart window, light shutter and display because of their unique property of being able to control the transmittance of light [6–9]. Electrochromic devices have a very high transmittance in their transparent state and hence, they are considered as strong candidates for the reflective part of a light-adaptable display. Typically, an electrochromic display consists of an electrochromic light shutter and a white reflector such as TiO_2 [10,11]. However, the performance requirements of the transparent emissive part of the light-adaptable display, such as a transparent OLED, preclude the use of white reflectors in these systems. Mirror reflectors are required as backside reflectors in light-adaptable display applications, and hence, they are used as an alternative to white reflectors. Nevertheless, new problems arise with the use of mirror reflectors. For instance, because of the specular character of mirror reflection, the viewing angle of the display becomes very narrow. Therefore, to improve the viewing angle of the display, an additional diffusion layer is needed on the surface of the display. This diffusion layer induces the blurring of images with the blurring width being proportional to the distance between the image plane and the diffusion layer. If this distance decreases, the blurring will also decrease. Ideally, if the diffusion layer coincides with the image plane, the diffusion-induced blurring of images disappears.

With these ideas in mind, an electrochromic device with diffusing function is proposed in the current study. With this kind of electro-

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* Corresponding author.
E-mail address: smcho@etri.re.kr (S.M. Cho).

http://dx.doi.org/10.1016/j.solmat.2017.04.021
Received 2 December 2016; Received in revised form 7 April 2017; Accepted 10 April 2017
0927-0248/

Please cite this article as: Cho, S.M., Solar Energy Materials and Solar Cells (2017), http://dx.doi.org/10.1016/j.solmat.2017.04.021

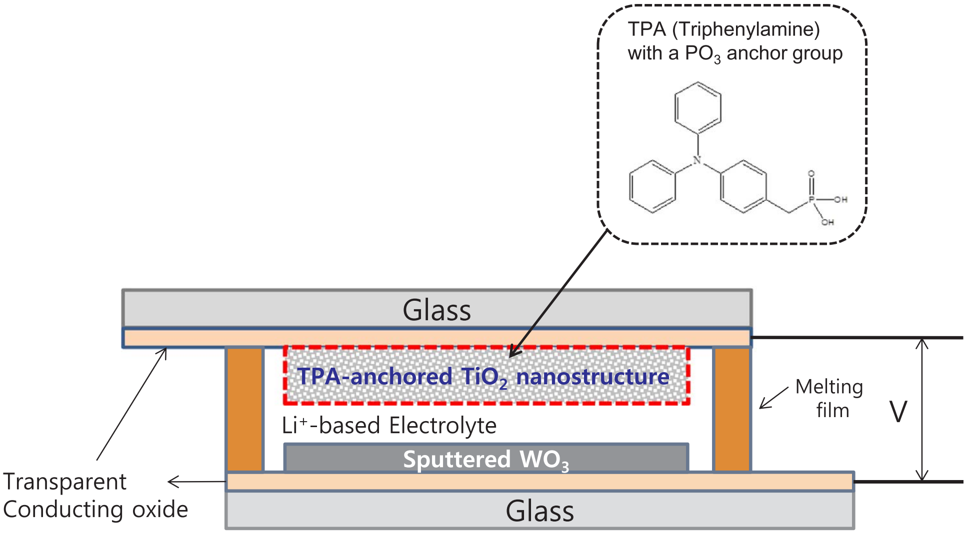

Fig. 1. Schematic diagram showing the structure of the TiO$_2$ nanostructure-based electrochromic device.

chromic device, the blurring of image can be minimized and the device fabrication, much simpler. In the present study, this kind of electrochromic device was developed by modification of a TiO$_2$ nanostructure-based electrochromic device, which has attracted much more attention because of its fast switching character [12–18].

2. Simulation

Fig. 1 shows the TiO$_2$ nanostructure based electrochromic device used in the present work. The TiO$_2$ nanostructure was formed with nano-sized TiO$_2$ particles (less than 20 nm). Triphenylamine (TPA) molecules were used as the anodic electrochromic (EC) materials [18,19]. The TPA molecules were modified to have a phosphate anchor group and fixed on the surface of the nanostructure with the anchor group. A sputtered tungsten oxide film was used as the cathodic EC material. The main aim of the present research is to impart the diffusing function to the device.

Two methods are proposed to achieve this aim. As shown in Fig. 2, the first approach is to make the electrolyte diffuse transmitting by adding some suitable scattering particles [Fig. 2(a)] while the second is to make the nanostructured electrode diffuse transmitting [Fig. 2(b)]. In the case of the former, no electrode modification is required. Hence, the fabrication process is very simple. However, problems regarding the stability of the scattering particles in the electrolyte arise. Specifically we observed some unstable electrochromic switching properties of the device with this structure in preliminary experiments. In the case of the latter, two kinds of particles are used to form the nanostructured electrode: nano-sized TiO$_2$ particles, which provide a high specific surface area for the adhesion of the electrochromic molecules, and submicron-sized the scattering particles, which provide the diffuse-transmitting function. In this latter structure, the scattering particles are fixed in the nanostructure, making the structure much more stable than that in the scattering electrolyte case. In view of this, the current work focuses on the latter type of structure [Fig. 2(b)].

According to the theory of light scattering, particle-induced light scattering phenomena are strongly influenced by the size of the scattering particles and can be classified into two categories: Rayleigh scattering and Mie scattering. Rayleigh scattering occurs when the size of the scattering particle is much smaller than the wavelength of the light (typically less than one-twentieth). The scattering has an isotropic character with very low efficiency. This implies that the backward and the forward scattering intensities are almost the same. In the present study, this is not a desirable character, because the backward-scattered light does not enter the device. As a result, the total transmittance of the device is decreased. If the particle size increases, the forward scattering increases, eventually leading to a transition from Rayleigh scattering (associated with smaller particles) to Mie scattering. This near-forward scattering is highly desirable in the present research. The contents of the scattering particles and the expected angular distribution of the scattered light can be roughly estimated by simulation. An open web MIE scattering calculator [20] was used to simulate Mie scattering, while the required optical constants of the TiO$_2$ nanostructure were estimated using the effective medium approximation method [21]. The volume fraction of the TiO$_2$ nanoparticles in the nanostructure was

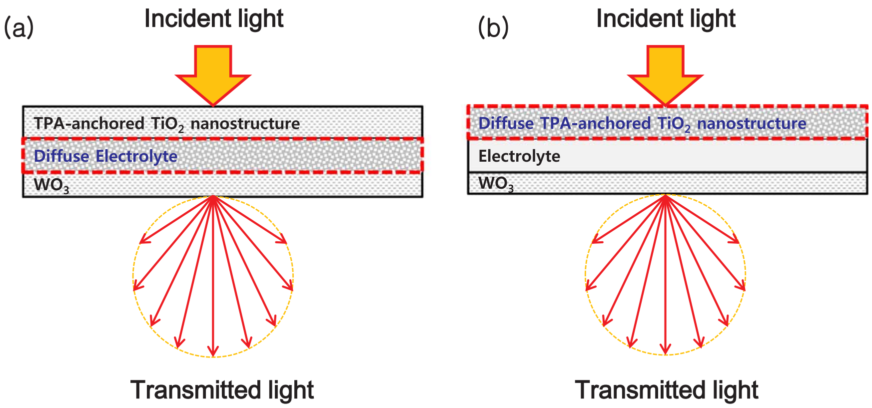

Fig. 2. Conceptual figures showing the methods to impart diffusing functions to the TiO$_2$ nanostructure-based electrochromic device; (a) scattering electrolyte scheme and (b) scattering electrode scheme.