Smart Window Based on Electrophoretic Display

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ABSTRACT
We fabricated a smart window based on electrophoretic display (EPD) technology, switching between white and transparent states by changing the stacking states of particles on the electrodes. Lateral driving EPD exhibits high transmittance, fast response, and high contrast ratio. This work demonstrated that EPD has great potential for practical smart windows.

1 Introduction
Smart windows can effectively and reversibly control the optical transmittance of natural light, which can efficiently reduce the energy consumption of buildings [1-3]. At present, most smart windows are based on polymer-dispersed liquid crystal (PDLC), electrochromic (EC), thermochromic, mechanoresponsive, and optical switching [4-8]. However, the practical application of smart windows based on these technologies is hindered by the long response time, low transmittance, high fabrication cost, and complicated preparation process [9]. Therefore, it is a challenge to develop smart windows with high transmittance and fast response speed.

The electrophoretic display (EPD) has obvious advantages, such as a high ambient contrast ratio which is suitable for outdoor display [10]; Bistability and low power consumption, which is suitable for long-term display [11]; Flexibility which can be used in flexible and stretchable electronics display [12]. Due to these advantages, EPD is widely applied in E-Book, electronic shelf labels, smart blackboards, etc. In addition, the electrophoretic particle can reflect and scatter the sunlight. It is feasible to fabricate the smart window based on lateral driving EPD. Eink Inc. reported a variable transparent shelf labels, etc. [13]. In this work, we fabricated a smart window based on EPD device driven by lateral fields, similar to in-plane-switching (IPS) type of wide-viewing angle LCD [15]. The smart window can switch between white (opaque) and transparent states by changing the stacking states of particles on the electrodes under 30 V driving voltage. Besides, we designed a special waveform for the lateral driven EPD. A series of shaking voltage is added before the DC 30V driving. Because of the high frequency, the small movement of the particles would not affect the white state display. Meanwhile, the small movement can improve the start-up speed of the electrophoretic particles, thus further enhancing the response speed of the device (400 ms). Lateral driving EPD exhibits high transmittance (78%) and high contrast ratio (Ttrans/Twhite = 89). This work demonstrated that EPD has great potential for practical smart windows.

2 Experiment

2.1 Preparation of the electrophoretic dispersion:
The electrophoretic dispersion was mixed with 0.5 g white TiO2 particles, 0.05 g OLOA 54720, and 9.5 g non-polar solvent Isorpar G. The electrophoretic dispersion was stirred at 500 rpm for 24 h.

2.2 Preparation of the PVA film and the electrophoretic test cell:
The different concentration PVA solution was spin-coated on the IPS electrode for 30 s at 1500 rpm and baked at 50 °C for 5 mins. The electrophoretic test cell was fabricated by IPS interdigital electrode coated with PVA film and ITO substrate. The thickness of the test cell was 40 μm controlled by OCA. The dispersion was filled into the test cell by capillary force. After injecting the
dispersion into the cell, two sides of the cell were sealed by an ultraviolet (UV) adhesive (NOA 60, provided by Norland) to prevent solvent evaporation.

3 Results and Discussion

The electrophoretic particles can be stacked and diffused on the electrode in lateral driving EPD under an electric field, achieving the transparent and color state reversible switching. Compared with commercial vertical driving EPDs, the lateral driving mode is easier to observe the microscopic motion behavior of the particles. Due to these unique properties, lateral driving EPDs can be used in smart windows, color e-paper displays, transparent displays, controlled privacy, sunglasses, etc., as shown in Figure 1.

Fig. 1 The lateral driving electrophoretic display applications in various fields. (re-drawn by summarizing the figures from ref.13, 16).

The working principle of smart windows is shown in Figure 2. The particles are evenly dispersed in the cell after filling the dispersion, and the device exhibits a white state. For the transparent state, the negatively charged TiO$_2$ particles will stack on the positively charged electrode under the electronic field, and the device shows a transparent state. To achieve the white state, the particles concentrated on the electrode would diffuse, and the device present a white state under a shaking voltage. In addition, to reduce the direct contact and adhesion of the particles with the electrode, we spin-coated a hydrophilic layer of PVA film on the electrode surface.

The SEM morphology of negatively charged TiO$_2$ white particles is shown in Figure 3. The TiO$_2$ particles show uniform spheres and average sizes of around 100-300 nm. Compared to previous research, our particle has a high zeta potential (-120 mV) and good homogeneity. White particles have a strong negative charge on their surface, making it easier to be driven, and develop the smart window’s response speed. Besides, the interface compatibility between PVA and ITO is also important. To improve the interfacial compatibility, we apply UVO-zone treatment for 20 mins on the ITO surface to improve its hydrophilicity. The contact angle is reduced to 10°, indicating that UVO-zone treatment can further improve the wettability of PVA solution on ITO. The SEM shows that the PVA layer is able to lay flat well on the ITO, shown in Figure 4. These results indicate that the interface between PVA and ITO is compatible.

Fig. 2 Schematic diagram of the smart window (a) white states (b) transparent states.

Fig. 3 The scanning electron microscopy (SEM) of TiO2 particles.

Fig. 4 The scanning electron microscopy (SEM) of PVA film particles.
To evaluate the optical performance of the smart window, we test the transmittance spectrum of the transparent smart window. Herein, we choose 20-180 μm (20 μm electrode width and 180 μm electrode pitch width) interdigital electrode as the electrode of the smart windows. It is worth noting that the pixel electrodes provided a strong guide for the future research of smart windows equipped with a TFT (Thin Film Transistor) array and achieve pixel driving. In addition, 20-180 μm is equivalent to 132 PPI (Pixels Per Inch) in pixel density which are the pixel electrodes that can be used in commercial display devices in future work.

The cell gaps would affect the electric field strength of the device, which further affects the response time and optical transmittance of the device, as shown in Figure 5. The transmittance of both transparent and white states decreases with increasing cell gaps. The transmittance curve of the transparent state decreased from 83% at 10 μm to 71% at 50 μm. Since the transmittance of white state decreases markedly as the cell gap increases, the smart window’s contrast ratio would increase from 2.4 to 96. The transmittance of the transparent state decreases due to the cell gap’s increasing, which weakens the electric field of the device, thus deteriorating the motion of the particles. To balance the transmittance and contrast ratio of a smart window, we choose 40 μm as the cell gap of the device.

The driving waveform would affect the activation of the particles. We designed a special waveform for the lateral driven EPD based on the direct DC driven. A series of shaking voltage is added before the DC 30V driving, which causes the small lateral movement of the particles near the electrodes, as shown in Figure 6. Because of the high frequency, the small movement of the particles would not affect the white state display. Meanwhile, the small movement can improve the start-up speed of the electrophoretic particles, thus further enhancing the response speed of the device [17]. As a result, the particles can be quickly driven, and the device achieves a fast response from the white state to the transparent state. We determine the approximate time by counting the video frames. The response time of the smart window is improved by adding the shaking voltage, shown in Figure 6.

To achieve the smart window transparent and pixelated display, we designed the pixelated electrode, as shown in Fig 7a. The pattern of pixelated electrode is
SYSU, and the aperture ratio is 88.56%. Besides, the photograph of the patterned driving smart window is shown in Figure 7b and 7c. The smart window can exhibit white states and obscure the underneath color without voltage. Obviously, the pattern “SYSU” can be well exhibited when the pixelated smart window is driven to transparent state under the voltage. The pixelated smart window can be used in the transparent and wearable display.

4 Conclusion

In conclusion, the smart window based on lateral driving EPD can achieve the transparent and opaque state by controlling the voltage. The device exhibited a high transmittance of 78%, high contrast ratio of 89, and a fast response time of 400 ms. Besides, we have achieved the smart window with pattern display based on pixelated electrode. These results demonstrated that the lateral driven EPD has great potential to be applied in smart windows, privacy protection, and optical switch.

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References


