Development of Transparent and Flexible Hydroxypropyl Cellulose Display

Edward S. Ju

The conventional smart window plays a passive role in reducing the sunlight entering the window by adjusting the transmittance of the transparent window. Recently, there has been a demand for the development of a next-generation smart window that can provide information in the form of an image through color change in a certain area of the window. In this study, a flexible and transparent hydroxypropyl cellulose (HPC) display was developed based on the thermochromic properties of HPC hydrogels. HPC changes its hydrophilic/hydrophobic properties based on its lower critical solution temperature (LCST, ~48.0 °C). Above the LCST, the molecular chains of cellulose, which are hydrogen-bonded to water molecules, break, causing cellulose molecules to agglomerate and resulting in white color formation. Based on this mechanism, a display image can be realized by increasing the temperature of a specific area of an HPC film by using a near-infrared laser. This technology will expand the application scope of future smart window technologies that require real-time information without the integration of complicated electric circuits.

I. INTRODUCTION

Smart window technologies comprise (a) passive smart windows that block or transmit sunlight depending on the rate of reaction of an incorporated chemical substance and (b) active smart windows that adjust transmittance using electronic circuits installed inside the glass [1,2,3,4,5]. Smart windows are made of glass, known as switchable glass. This glass involves tinting, allowing it to change its reflective properties for both privacy and prevention of excessive sunlight and heat. Since passive smart windows do not use electric circuits, fabrication is simple. An additional energy source is not required. However, it is difficult to intentionally shield or transmit sunlight in passive smart windows because the thermochromic materials react sensitively to changes in ambient temperature [1,2]. Active smart windows can control the amount of light or heat entering a room by blocking or transmitting sunlight by simply turning a switch on or off. However, because the electronic circuits for driving the active smart window require many fabrication processes including laminating and patterning, the manufacturing costs are high, and electrical wiring is required for installation and daily-use of passive and active smart window displays [3,4,5]. To overcome such limitations, a novel conceptual smart window display is proposed that is simple to fabricate and operate, can block sunlight in a specific area, and can display information if necessary.

This study aims to investigate a novel smart window display that combines the advantages of passive and active smart windows by using hydroxypropyl cellulose (HPC) that responds to infrared (IR) heat. The concentration and thickness of HPC were optimized by observing changes in thermochromic properties of HPC according to the applied IR heat. The optimal driving characteristics of the fabricated HPC display were investigated. This technology can be applied to develop an intelligent window display that provides specific information via color changes to improve air-conditioning efficiency, privacy protection, and light reflection, as well as express images on the display.

II. METHODS

Preparation of HPC solution. HPC (MW ≈ 100,000, Sigma-Aldrich) was mixed with deionized (DI) water at concentrations of 7.5, 10.0, 12.5, and 15.0 wt%. The HPC–deionized (DI) water solution was placed in a 50 ml conical tube and mixed using a centrifuge for ~2 min. Initially, the solution was foamy and non-uniform; however, after ~10 min, upon sufficient HPC swelling, a transparent, high viscosity solution was achieved.

Fabrication of HPC displays. A near-IR (NIR) absorption-heating film (CR70, 3M) was attached to top of a polyethylene naphthalate (PEN) film (Teonex Q65HA, Teijin DuPont Films); a double-coated tape (9495LE, 3M) was attached to the border of the NIR absorption-heating film with a width of 2 mm. To control the thickness of the HPC film, the double-coated tape was attached at four different thicknesses: 170 µm (Thickness (T)1), 340 µm (T2), 510 µm (T3), and 680 µm (T4). After coating the HPC solution with the same thickness as that of T1–T4, it was covered with a PEN film (Fig. 1).

Operation of HPC displays. A NIR laser marking machine (Mini1064-30, Changchun New Industries Optoelectronics Tech. Co.) was used for NIR irradiation (1064 nm). The NIR laser beam (0.39 W) was scanned along the pattern path of various images and letters on the surface of the HPC display substrate using EZCAD2 software (Beijing JCZ Technology Co.). The temperature change was measured with an IR camera (T420, FLIR Systems, Inc.), and the change in luminance was extracted using a video analysis and modeling tool (Tracker, http://physlets.org/tracker).

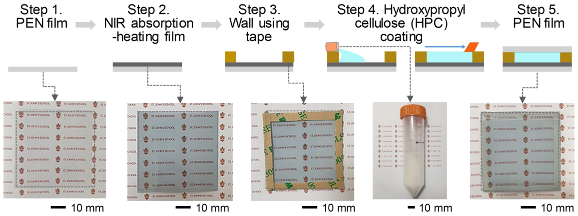

Figure 1. Fabrication of the hydroxypropyl cellulose (HPC) display.

III. RESULTS AND DISCUSSION

The color of HPC in water is changed according to hydration and dehydration. Accordingly, the transparent-opaque color conversion of the HPC was performed by changing the concentration and thickness of HPC. Figure 2(a) shows the thermochromic properties of HPC as a function of temperature. Because HPC is hydrophilic at room temperature, it is well dispersed in water as hydrated cellulose and appears transparent. Above the lower critical solution temperature (LCST, ~48.0 °C), HPC becomes hydrophobic and dehydrated cellulose acts similar to particles and its chains get entangled. Therefore, the HPC solution in water appears opaque white. As shown in Fig. 2(b), the HPC solution at temperatures lower and higher than the LCST shows a transmittance of ~40% and 0%, respectively, in the visible-light region.

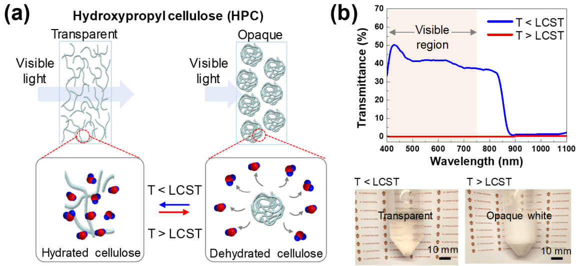

Figure 2. (a) Schematic of HPC at temperatures lower (left) and higher (right) than the lower critical solution temperature (LCST). (b) Transmittance characteristics and photographs of HPC (15.0 wt% in water) at different temperatures.

The optimum mixing ratio was found by changing the concentration of HPC in DI water. The HPC film produced at the four different concentrations (7.5, 10.0, 12.5, and 15.0 wt%) was irradiated with an NIR laser at intervals of 20 s to confirm whether it became opaque white. A line-shaped image with a length of 10 mm was formed upon NIR laser irradiation (1064 nm, 0.39 W). As shown in Fig. 3(a), the color began to change to white when the HPC concentration was ≥12.5 wt%. Thus, the HPC concentration was optimized at ≥12.5 wt% at which cellulose aggregation is observed. At 15.0 wt% HPC, the white color was more vivid. At higher concentrations, the transparency of the HPC solution decreases even before the temperature is increased, and the transparent-opaque transition rate is decreased. Therefore, the HPC concentration was optimized at 15.0 wt%, and the changes in the display brightness according to the thickness of the HPC film were examined (Fig. 3(b)).

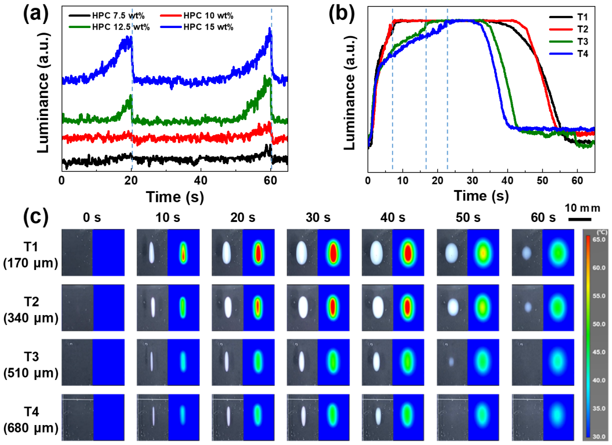

Figure 3. Temperature and luminescence characteristics of a line pattern image formed by varying HPC concentration and HPC film thickness. Luminance change as a function of (a) the HPC concentration and (b) HPC film thickness. (c) Visible-light and thermal-IR images as functions of the HPC film thickness.

i. The time to reach maximum luminance is dependent on the thickness of the HPC film. T1 and T2 had a similar time of 7.2 s, while those for T3, T4 were 17.1 and 22 s, respectively. Figure 3(c) shows the luminescence and temperature characteristics at different HPC film thicknesses. At 10 s, white patterns were formed in T1 and T2, whereas faint thin white patterns were observed in T3 and T4. T3 and T4 did not receive sufficient heat even after 20 s. Accordingly, T1 and T2, which exhibit fast luminescence characteristics, appeared to have an appropriate thickness. However, in the case of T1, it was difficult to uniformly coat a large-area substrate because of its thinness and unexpected abrupt changes that may occur upon an increase in temperature. Therefore, T2 was selected for further analysis.

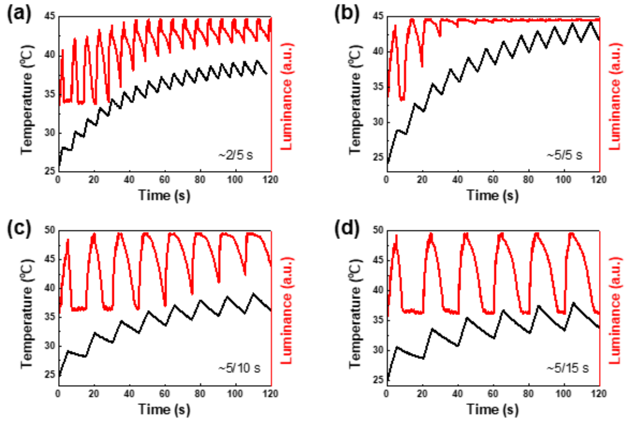

Figure 4. Temperature and luminance characteristics of a line pattern image formed by varying the time interval of the NIR laser irradiation on a HPC film. (a) Turn on/off time of ~2/5 s. (b) Turn on/off time of ~5/5 s. (c) Turn on/off time of ~5/10 s. (d) Turn on/off time of ~5/15 s.

Figure 4 shows the temperature and luminance characteristics of HPC according to the time interval of irradiating a NIR laser to HPC. At the turn on/off times of 2/5 s and 5/5 s, the luminance remained at a constant level due to the continuous accumulation of heat. When the turn off time increased to 10 s, the luminance graph tended to become more stable. However, even the 5/10 s graph showed an increase in luminance as the operation time increased. On the other hand, in 5/15 s, the luminance became more stable even after a long operation time.

Figure 5 shows the operation and display performance of the HPC film. An NIR laser beam (1064 nm, 0.39 W) was scanned along the pattern path of various images and letters on the surface of the HPC display substrate (50 × 50 mm^2). As shown in Fig. 5(a), various white image patterns (star, tree, USA letters, Sigma character) can be displayed on the HPC film. Figure 5(b) shows the captured video image of the HPC display, which shows real-time changes in the images.

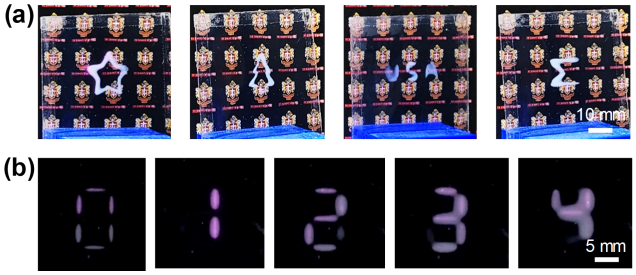

Figure 5. (a) Four representative images and letters formed on the HPC display substrate. (b) Captured video images of the HPC display.

IV. CONCLUSION

In summary, this project proposes an information-providing smart window technology that can express text and images in real-time. A structure of cellulose and NIR absorption-heating film was created inside two transparent and flexible PEN films. When the HPC display was irradiated with a NIR laser, the NIR absorption-heating film reacted with NIR light, causing the temperature to rise rapidly and heat to be transferred to the HPC in contact with the NIR absorption-heating film. When the temperature of HPC rose above LCST, the water molecules interact with cellulose, causing the white visual appearance. This technology can help develop a flexible and transparent display at low cost without using electronic circuits [3,4,5,6,7]. Because there is no restriction to the substrate structure, desired information can be freely formed not only in a flat display, but also in a curved and flexible display. Additional research is needed to rapidly improve the response time of the HPC device structure and driving method. The fast response and selective blocking/permeation function of this novel display has the potential to impact various fields, including the information-provided transparent glass windows in automobiles, spaceships, subways, shops, and restaurants.

V. Acknowledgment

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VI. References

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