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Multiple guidance of light using asymmetric micro prism arrays for privacy protection of device displays

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Abstract: With increasing use of mobile displays outdoors, privacy-related issues have come to the fore. Therefore, in this study, we proposed a novel concept using directionally guided light transmission using double-sided asymmetric prism arrays for fabricating a privacy protection film for digital displays. The proposed film allows only the user in front of the display to see its contents using dual refraction in a prism array. Otherwise, when the display is viewed at an angle, it is difficult to recognize the contents due to the overlap of different letters. The optical path was analysed through ray-tracing simulations, and the performance of the film was quantified using an optical character recognition (OCR) method. To further enhance the effectiveness of the film, a metal film was applied on the vertical face of the micro prism arrays using an oblique deposition method. This metal-coated double-sided prism array film showed superior privacy-protecting performance compared to a conventional method based on the micro-louver structure.

1. Introduction

Modern consumers are increasingly using their display devices (mobiles, laptops, etc.) outdoors, such as while commuting on the bus, in trains, or when travelling in an aircraft. Privacy and security take centre stage during such use cases. To minimize the ability of others to see our secure information, privacy protection films, which can be seen only in front of the device, have been developed and commercialized [1–3]. Such privacy films utilize micro-louver technology and contain micro-line patterns with a high aspect ratio that are closely arranged together to block the screen contents when viewed from an angle [1–3]. The lines are filled with light-absorbing dyes to block the screen's content when viewed at an angle. To fabricate these structures, nanoimprint lithography can be utilized [4–6]. After the preparation of a master containing micro line patterns with a high aspect ratio, polymers are filled into the void of the master and applied by pressure, heat, or ultraviolet (UV) light. However, it is difficult to fabricate high-aspect-ratio patterns using polymeric materials due to the lateral collapse of the line patterns [7,8]. To avoid this issue, either the pattern height is limited, or the Young's modulus should be high to maintain the line structures [7]. However, when the polymer structures have a high modulus, it becomes difficult to detach the polymeric patterns from the master [8]. Filling ink into the void patterns is another challenge that increases the complexity of fabrication. Recently, a high-transparency privacy protection concept using distortion of image through reflection on microcubic surfaces was reported [9].

It is based on the concept of overlapping different images to original ones by the reflection on the surface of micro-cubic structures without coating opaque materials to obtain a high transmittance.

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However, the distortion produced was not perfect in preventing other people from seeing the screen at an angle. In this study, we proposed a novel method for fabricating a privacy-protecting film that uses multiple directional light guidance with a double-sided asymmetric micro prism array. The concept of directional light guidance through asymmetric prism arrays has been used in optical films for 3-D displays and for fabricating asymmetric structures by combining with photolithography for applications in microfluidics [10,11]. In this research work, we realised double-sided asymmetric prism arrays, which allow the device user in front of the display to be able to clearly see it due to the double-refraction through the prism array. However, when viewing from an angle, the light gets reflected on the prism surface, which distorts the image contents of the display. Through experiments, we learned that a higher film thickness and refractive index would be more effective for privacy protection due to the increase of the overlap of different letters. To quantitatively analyse the distortion effect, an optical character recognition (OCR) method [12] was used to count the number of letters seen clearly. To enhance the performance of the film, we deposited a metal film on the vertical plane of the asymmetric prism array through an oblique metal deposition [10]. Thus, the proposed privacy protection film uses blocks light as well as distorts to obscure contents of the screen when viewed from a side angle.

2. Results and discussion

Figure 1(a) depicts a schematic illustration of the experimental procedure used to fabricate the double-sided asymmetric micro prism arrays through UV nanoimprint lithography. First, we prepared a metallic asymmetric micro prism array master (Fig. 1(b)) through micromachining. After fabricating the master, we poured UV-curable polyurethane acrylate (PUA) prepolymer with three different refractive indices (1.6 HRP PUA, 1.5 MRP PUA, and 1.4 LRP PUA) on the master and placed a polyethylene terephthalate (PET) film on the prepolymer. After curing the PUA using UV (λ=365nm) for 4s, we detached the polymeric asymmetric prism film from the metallic master, as shown in Fig. 1(c). After preparing two asymmetric prism arrays, we bonded them together by inserting the optically clear PUA liquid (1.5MRP) and curing it using UV light for 10s. Figure 1(d) shows a scanning electronic microscope (SEM) image of the double-sided asymmetric micro prism array. Figure 1(e) shows a microscopic image of commercial privacy film based on micro-louver method (3M, PF12.5W9). The width of the lines is 10 µm, the spacing is 50 µm, and the height is 150 µm.

Figure 2(a) presents a schematic representation of our concept to test the privacy protection performance. After preparing the film, we placed it on a display device showing the university logo and observed its performance from various viewing angles. Figures 2(b) and 2(c) show the selected ray paths obtained from the ray-tracing software (Ray Optics Simulation). When viewing the display from the front, the rays are refracted twice, and the user is able to see the display device clearly (Fig. 2(b)). However, when viewing the display from an angle, it is difficult to recognize the contents due to the overlap of different letters as shown in Fig. 2(c). For example, the "X" letter can be observed in two positions and the distance of the positions is proportional to the thickness (t) of the film. The "O" letter separated from the distance can be overlapped to the "X" letter and it is the reason of the distortion of the contents. Figure 2(d) shows photographs taken from various viewing angles (–60°, –30°, 0°, 30°, 60°) when we used three samples with different film thicknesses. From the front, the image can be seen clearly in all samples. However, the images seen from an angle are distorted because of the overlap of different images predicted in Fig. 2(c). Also, the distance of observed images is increased with increasing the film thickness (t) as shown in Fig. 2(d). We note that the image inversion due to the reflection on the surface was not significant because the prism size (~30 µm) is much smaller than the letter size as discussed in the literature [9].

To verify the effect of total reflection on image distortion, we conducted experiments on materials with different refractive indices (1.4, 1.5, and 1.6). We used these materials fabricate

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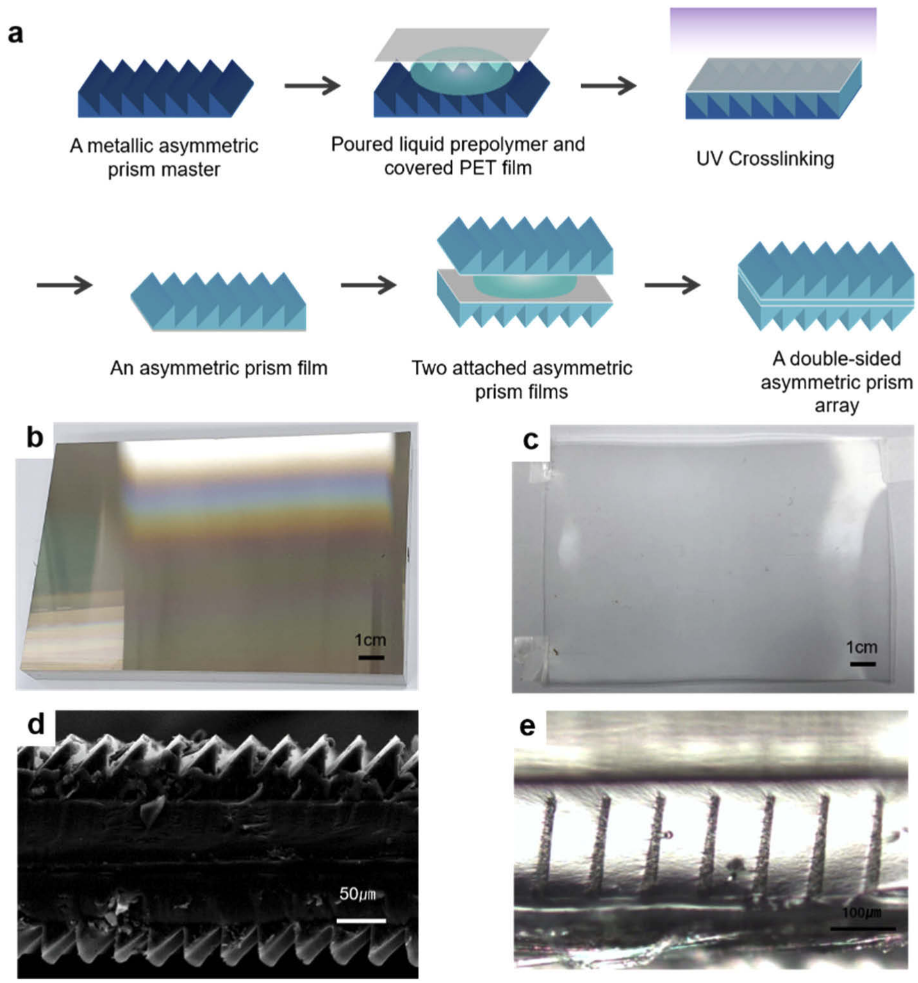

Fig. 1. Fabrication of a double-sided asymmetric prism array. (a) Schematic illustration of the experimental procedure for fabricating a double-sided asymmetric micro prism array. (b) Metallic master for asymmetric prism arrays. (c) An asymmetric prism film fabricated using transparent polymer PUA material. (d) SEM image of a double-side asymmetric prism array (scale bar: 50 μm) and (e) SEM image of a micro-louver-based privacy film.

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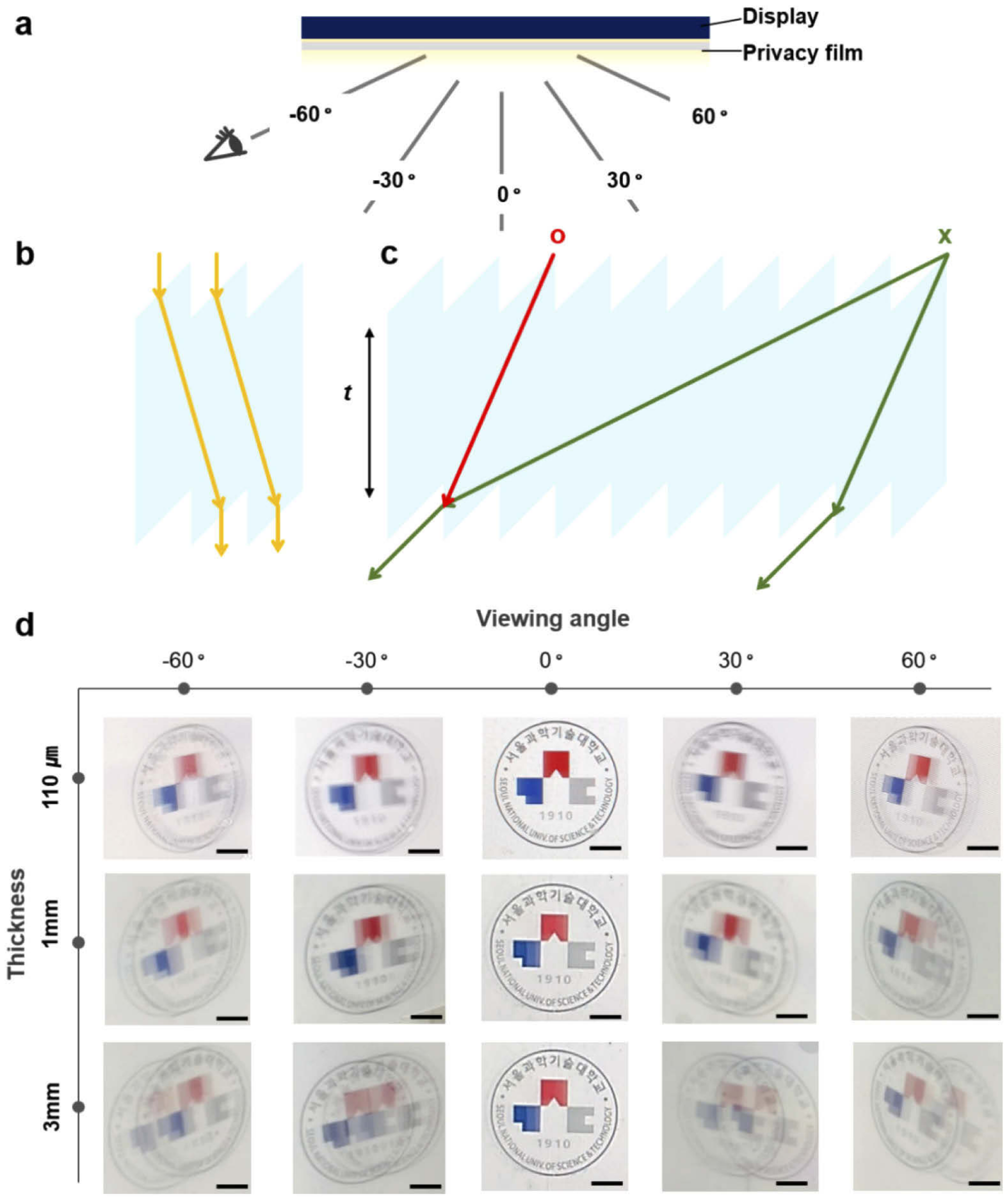

Fig. 2. Characterization of a double-sided asymmetric prism array. (a) Schematic representation of the measuring viewing angle method. (b) Optical ray-tracing simulation of the double-sided asymmetric prism arrays in the frontal view. (c) Optical ray-tracing simulation of the double-sided asymmetric prism arrays at a side view. (d) Sample image on a digital display as seen through the three films with different thicknesses (scale bar: 1 cm) at various viewing angles (–60°, –30°, 0°, 30°, and 60°).

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double-sided asymmetric micro prism arrays and then compared their performance at different viewing angles. Figure 3(a) shows a picture of the university address (Seoul National University of Science and Technology Chungwon-gwan, 232 Gongneung-ro, Nowon-gu, Seoul 01811, Korea) taken at different viewing angles through the three films with different refractive index conditions. At viewing angles of –60° and 60°, it is difficult to read the letters because of image distortion in all the three films. However, at viewing angles of –30° and 30°, it can be seen that the distortion increases with the increasing refractive index. An optical character recognition (OCR) has widely used in image scanners that capture image of printed letters and convert them into machine-readable letters [12]. To quantify the image distortion, we used OCR method and measured the accuracy rate (AR) of the letters in the images. To calculate AR, we used Google drive's OCR. After taking pictures at the viewing angle (–60°, –30°, 0°, 30°, and 60°),

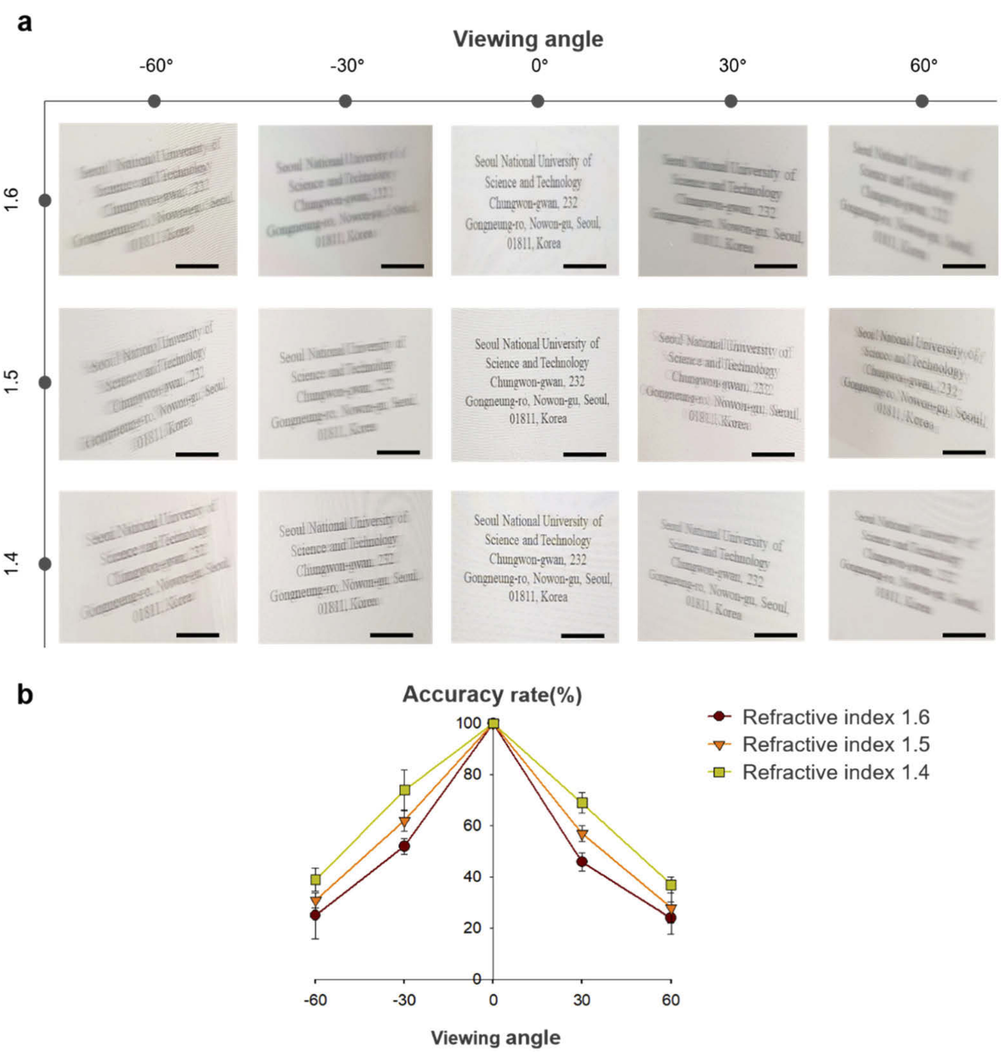

Fig. 3. Characteristic analysis of double-sided asymmetric prism array films. (a) The same sample image seen through the three films of different refractive indices (scale bar: 1 cm). (b) AR graph (%) showing the relation of refractive index versus the viewing angle (−60°, −30°, 0°, 30°, and 60°).

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we uploaded them to Google drive. Then, we converted the picture to letters using the OCR and manually counted the number of correctly recognized letters to assess AR. Figure 3(b) plots the AR readings (%) against the viewing angles for the three films based on the images in Fig. 3(a). It can be observed that AR decreases with the increasing refractive index. Furthermore, it decreases with an increase in viewing angle. However, we note that AR is 100% in all refractive index conditions when the viewing angle is 0°.

To further enhance the light-blocking performance of our film, we deposited a metal film on the vertical face of the asymmetric prism arrays through oblique metal deposition, as shown in Fig. 4(a). The upper part of Fig. 4(b) shows pictures taken at viewing angles of –60°, –30°, 0°, 30°, and 60 through our film. It is evident that after metal deposition, the film shows a light-blocking effect and the contents of the display cannot be seen at –60° and 60° viewing angles. Additionally, the film still shows image distortion at –30° and 30°. The lower part of Fig. 4(b) shows the performance of a conventional privacy protection optical film (3M, PF12.5W9) that uses high-aspect-ratio micro-louver structures. It can be observed that in the commercial film, the light gets completely blocked at viewing angles of –60° and 60° and partially blocked at viewing angles of –30° and 30°, which is similar to our results. However, there is no image distortion effect seen in the commercial sample.

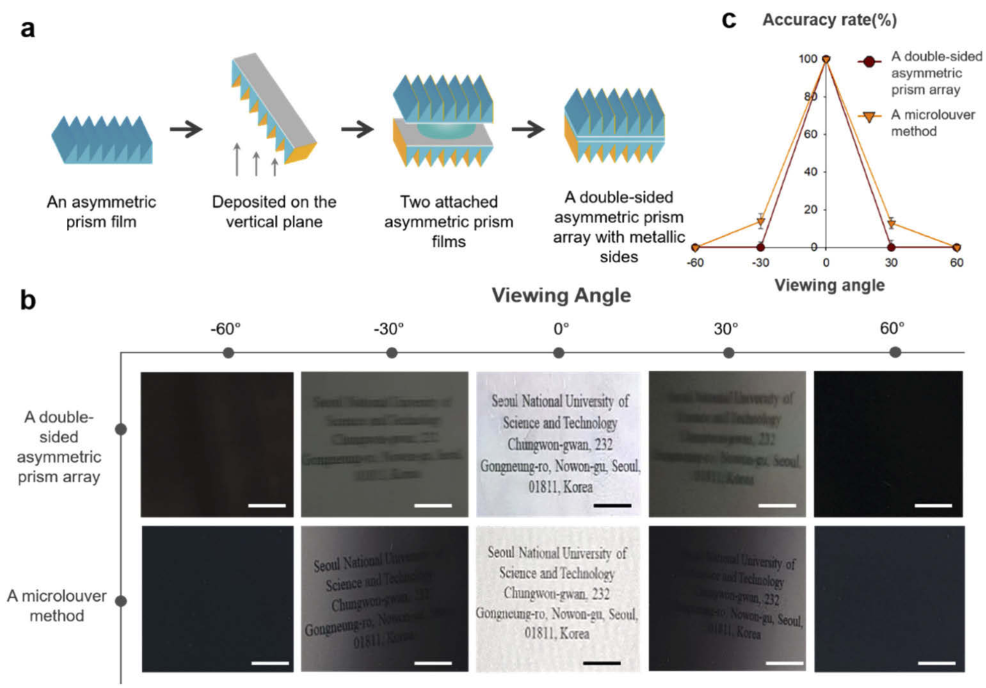

Fig. 4. A metal film-coated double-sided asymmetric prism array film. (a) Schematic representation of a double-sided asymmetric prism array with metal deposition on the vertical plane. (b) Sample image seen through the proposed film with metal deposition (scale bar: 1 cm) at various viewing angles. (c) AR graph (%) comparing the proposed film with the conventional product based on the micro-louver method.

Figure 4(c) compares the AR results of both the films, and it can be observed that AR of the proposed film is lower than that of the conventional sample at viewing angles of –30° and 30° which means that it is more difficult to see contents of the underlying display through the film we proposed. To further compare the performance between the micro-louver structures and

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the double-sided prism arrays after metal deposition, we compared their transmittance and the critical viewing angle at which they start to block light.

As can be seen in Fig. 5(a) and, the micro-louver has design parameters such as width (w), space between lines (s), and height (h). Therefore, the transmittance (T) and critical viewing angle (θ_c) of the design in an ideal case are given below.

$$T_{line} = 1 - \frac{w}{s + w} \tag{1}$$

$$\theta_{c,line} = arctan\left(\frac{s}{h}\right) \tag{2}$$

We note that the transmittance is defined as the ratio of the transparent area to the total area. The design parameters of the asymmetric prism array film include the prism angle (α) and refractive index of the prism (n). In the case of an asymmetric prism array, transmittance can be obtained as follows:

$$T = 1 - \frac{\mathrm{a}}{\mathrm{A}} = 1 - \frac{\cos\alpha \ * \ \cos(\alpha + \beta)}{\cos\beta} \tag{3}$$

where A is the length of the hypotenuse of a prism ($A = h/cos\ \alpha$), a is the length of the region to be reflected by a metal film ($a = h\frac{\cos(\alpha+\beta)}{\cos\beta}$), and h is the height of the prism.

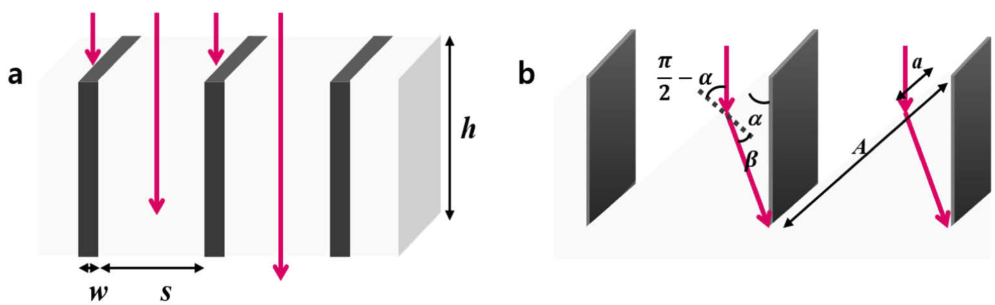

Fig. 5. Schematic illustrations representing the design parameters. (a) High-aspect-ratio micro-louver structures. (b) Asymmetric prism arrays for privacy protection.

When the prism angle is 45° and the refractive index is 1.5, the calculated transmittance in the ideal case is 76%. With regard to fabrication complexity, the prism patterns are mechanically robust compared to the high-aspect-ratio micro-louver patterns to avoid the lateral collapse issue [7,8], and oblique metal deposition has been widely used for fabricating special optical films [13–16].

In Table 1, we compare the performance in terms of the accuracy rate and the transmittance of the proposed double-sided asymmetric prism array film (with and without metal deposition) and the conventional film based on the micro louver method. It can be seen that in the case of the proposed film, accuracy rate (AR) decreases, which means the privacy protection becomes stronger, when the asymmetric prism array is coated with a metal film. However, the transmittance at 0° without the metal deposition is much higher compared to the other two films (both of which show 70% transmittance). In addition, it can be observed that the accuracy rate at viewing angles of –30° and 30° in the proposed film with metal deposition is 13% lower than that of the film based on the micro-louver structures.

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Table 1. Comparison of privacy protection performance

Type of privacy film	AR average of –30 ° and 30 ° [%]	AR average of –60 ° and 60 ° [%]	Transmittance [%]
Proposed film[a]	62	33	80
Proposed film with metal deposition	0	0	70
Commercial film based on micro-louver structures	13	0	70

[a]Double-sided asymmetric prism array film with a refractive index of 1.5

3. Experimental section

We designed micro asymmetric prism array structures with a period and height of 30 µm and an angle of 45°. The metal master was fabricated using a mechanical micromachining method. After the preparation of a stainless steel block electroplated with nickel metal, the surface was mechanically machined using a diamond-cutting tool with the desired angles and pitches. After the master fabrication, we used PUA prepolymer (Material Chemicals Network Co., Ltd) with three refractive indices (1.6 HRP PUA, 1.5 MRP PUA, and 1.4 LRP PUA) and placed a PET film as a substrate. After UV curing (λ = 365nm) the PUA for 4s using Fusion Cure 360 (Minuta Tech., Republic of Korea) in 5.0 mW$/cm^2$, we detached the asymmetric prism array film from the metallic master. After fabricating two such films, a transparent 1.5 MRP PUA liquid prepolymer was inserted between the films and cured with UV light to bond them together. Scanning electron microscopy (SEM) images were obtained using an EM-30 scanning electronic microscope (Coxem, Republic of Korea) with an acceleration voltage of 10 kV. We coated aluminum metal with a thickness of 100 nm on the vertical plane, using a thermal evaporator in a high vacuum. For the experiments, the metal was placed on a tungsten boat at a vacuum degree of 7×10^{-4} torr and, under an applied current, the metal sublimated to a gaseous state and adhered to the film surface. An inclined loader was used to define the oblique angle. The deposition rate was 0.1 nm/s. The transmittance through the films was measured using a window tint metre (AT-173, Guangzhou Amittari Instruments Co., Ltd.). We used PUA with a refractive index of 1.5 to predict the effect of the refractive index on the clarity of the optical film and conducted an optical simulation (Ray Optics Simulation) to analyse the optical path through the dual-side asymmetric prism arrays. We used the OCR test provided by Google Drive to count the number of letters that could be read correctly using the OCR's text converter (https://www.google.com/intl/ko_ALL/drive/). We took a picture with a smartphone (Samsung Galaxy S10e) and conducted the OCR test by uploading the picture on the Google Drive website. When converting the picture into text, the letters were recognised, and we counted the number of correct letters manually.

4. Conclusion

We proposed a method for fabricating privacy protection films using dual directional light guidance with double-sided asymmetric micro-prism arrays. Moreover, through optical ray-tracing simulations, we analysed the effects of distortion of light on the asymmetric prism arrays for different refractive index values and were able to confirm that the privacy protection performance improves when using materials with higher refractive indices. To enhance the privacy protection performance of the proposed film, we carried out an oblique metal deposition on the vertical face of the asymmetric micro-prism arrays to further block the passage of light. For an objective assessment of performance, we then carried out OCR tests on the proposed film and compared it against the performance of a commercially available privacy protection film. Through the experiment, we were able to confirm that the proposed film, through its combination

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of image distortion and light-blocking effects, showed superior performance when compared to the film fabricated using micro-louver structures.

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Disclosures. The authors declare no conflicts of interest.

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