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Communication

Directional Amplification of Luminance and Formation of Complex Structures by Using Reflective Janus-Faced Prism Array

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Introduction

Optical design is of great importance in optical devices such as lightings, solar cells, and display devices and thus should be optimized in order to maximize their efficiencies. Applications that use flat-panel displays (FPDs) make use of microstructures to achieve high performance.[1-9] In the case of organic light emitting diodes (OLEDs), the light extraction efficiency is ~20% because the light is confined to high-refractive-index materials such as the active organic materials, indium tin oxide, etc. To extract the light, there have been approaches using micro patterns to scatter the reflection on the active materials.[1-3] For solar cell applications, texturing and nanowire structures have been used to trap incident light to enhance the current density.[4,5] To enhance the brightness of liquid crystal displays (LCDs), brightness enhancement film (BEF), which has a function of collimating incident light to the frontal angle, has been used.[6] However, there has been few attempts to optimize efficiencies in lighting applications by FPDs such as OLEDs. In the application of conventional lightings such as light bulbs and fluorescent lamp tubes, there have been numerous reflector designs to enhance luminance by sacrificing light rays in the backside and adding them in the frontal direction.[7-9] However, the reflector design should be limited in FPDs which is a two-dimensional light source, thus there have been only reflective films in the backside. Here, we propose a strategy to enhance the luminance from FPDs in a specific direction by placing a specially designed optical film. We have prepared a reflective Janus-faced prism array by coating reflective metal film on one face of each prism and used it to reflect the incident light in an undesirable direction to a specific direction. To prove the amplification of the luminance in a direction, we measured the luminance in all directions and explained by an optical simulation. Also, the directional allocation of incident light by reflective Janus-faced prism array can be employed to fabricate asymmetric structures by combining photolithography and the optical film. Especially, we can manipulate the structural design by controlling parameters such as the space between patterns and exposure time to fabricate coffee-pot structures or bullet cartridge belts.

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Experimental

Fabrication of Reflective Janus-Faced Prism Array. At first, we prepared metallic masters by mechanical machining. To begin with, a blank plate of nickel electroplated stainless steel was prepared. Then, the surface was processed by machining with a diamond cutting tool. During the process, the design of the prism array such as pitches and prism angles were determined. In this study, we used a prism array with 50 μm in the period and 45° of the prism angle. After the master fabrication, we dropped photo-curable polyurethane acrylate prepolymer (PUA, 301RM, Minuta Tech)[10] onto the master mold. After the ultra-violet (UV) exposure for crosslinking the PUA, we detached the polymeric prism film from the metallic master. Then we coated reflective aluminum films of 20~100 nm in thickness on one face of the prism array by oblique metal deposition. A thermal evaporator in a high vacuum was used for the experiments. To define the oblique angle, an inclined loader was used.

Simulation of Light Rays. A commercial software package (LightTools) was used for the optical simulation. We performed the simulation to trace the rays injected from a 2-dimensional Lambertian light through to a prism array which has 3 prisms (50 μm in the period, 5 mm in length) with a refractive index of 1.5.

Fabrication of Directionally-Oriented Structures. First, chromium-sputtered (100 nm thickness) glass substrates were prepared. Then, chromium (Cr) film was patterned by conventional photolithography and wet etching with a Cr etchant (CR-75, chromium photomask etchant, Cyantek Corporation). On the glass substrate coated with patterned Cr film, a negative-type photoresist (DNR-H200PL, DONGJIN SEMICHEM) was spin-coated to ~10 μm in thickness. To disproportionate the light intensity, we inserted the directionally reflective prism sheet between the UV source of mask aligner (MDA-400M, MIDAS System) and the photoresist (PR)-coated glass substrate. After the UV exposure for 30~90 seconds, the sample was annealed on a hot plate (110 °C) to fix standing wave problem (post-exposure baking). The development was carried out with diluted tetramethyl ammonium hydroxide (TMAH), leaving behind the cross-linked regions of the negative PR.

Results and Discussion

Figure 1(a) shows a schematic illustration of the fabrication of reflective Janus-faced prism array. At first, we prepared a transparent polymeric prism array film by a replica molding from a metal master fabricated by mechanical machining. On the transparent prism film, we coated 20~100 nm of reflective aluminum films on only one side of the prism array with oblique metal deposition. Then, we obtained a prism array of which one side is reflective while the other is transparent. The detailed experimental procedure could be found elsewhere.[11-13] Figure 1(b) shows the pictures of a university logo on an LCD monitor through the designed optical film. From the right side, the background of the logo is dark compared with the screen outside the film. From the left, the area of the logo is brighter than the rest of the screen. It is because the incident light on the right side is reflected and scattered to left direction and the guided rays enhance the luminance in the left direction.

To quantitatively measure the luminance enhancement, we used a spatial photometer (EZ-Contrast 160R, ELDIM) and obtained isoluminant contour graphs. Figure 2(a) shows luminance distribution through all viewing angles when we use a conventional prism array, which is not coated by reflective metal films. Due to the refraction of incident ray on the faces of the prism array, the left and right sides from the center show higher luminance than the center line. When we use the reflective Janus-faced prism array, the left side shows the higher luminance than the right side or the center line as shown in Figure 2(b). With the comparison of the luminance with normal and the reflective Janus-faced prism arrays, we could confirm that there is an amplification of the luminance by ~6% (Figure 2(c)). The difference of the total intensity through the normal prism array and the reflective prism array originates from the scattering effects due to the roughness of the prism surfaces.

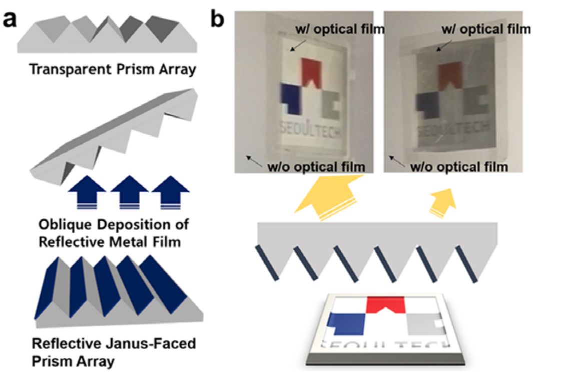

Figure 1. (a) An illustration of the fabrication procedure of the reflective Janus-faced prism array. After preparing a transparent prism array, reflective metal films are deposited onto one face of each prism. (b) Pictures of a university logo through the designed prism array taken from the left and right sides. The property of the directionally reflective prism array is to make a portion of an area much brighter than the rest of the area by the compensation for the loss in the right direction.

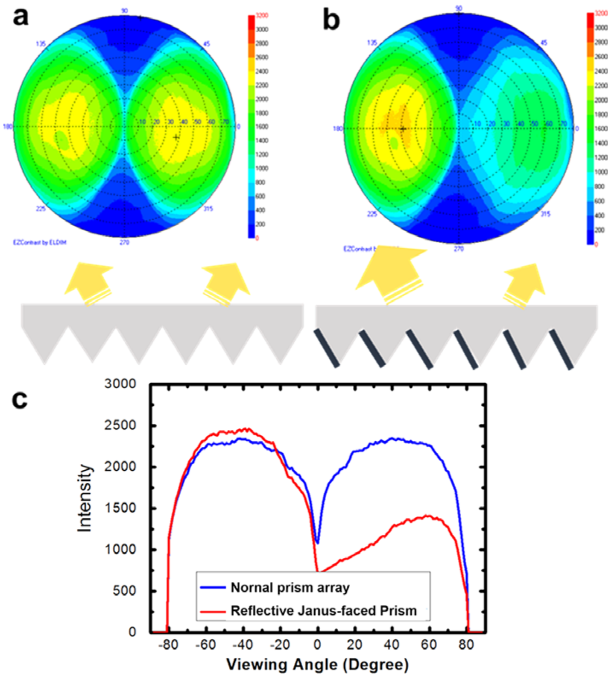

Figure 2. (a) An isoluminant contour graph through a normal prism array film. Incident lights are divided into two directions equally. (b) An isoluminant contour graph through a reflective Janus-faced prism array film. (c) A graph comparing the intensity distribution of normal and directionally reflective prism arrays.

To explain the experimental results, we performed an optical simulation with commercial software (LightTools). Figure 3(a) shows that the schematic for the simulation. We put the experimental parameters such as the period (50 μm), the prism angle (45°), refractive index (1.5). We can predict the deviation angle by the Snell's law, which is given as follows,[14,15]

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (1)$$

where n_1 and n_2 are the refractive indexes of air and a polymer material, θ_1 and θ_2 are the angles of incident and refracted light, respectively. From the model, we can derive θ_2 as ~22° with values of n_1~1, n_2~1.5 and θ_1~45°. As the eq. (1) predicted, the deviation angle can be manipulated by changing the prism angle. Also, we designed the prism array with three prisms for the optical simulation (Figure 3(b). It is noted that the simulation results with more than 3 prisms show similar trends. As a 2-dimensional light source, we used a lambertian source and the maximum luminance is over 30 candelas in the centerline (Figure 3(c)). Then, we obtained

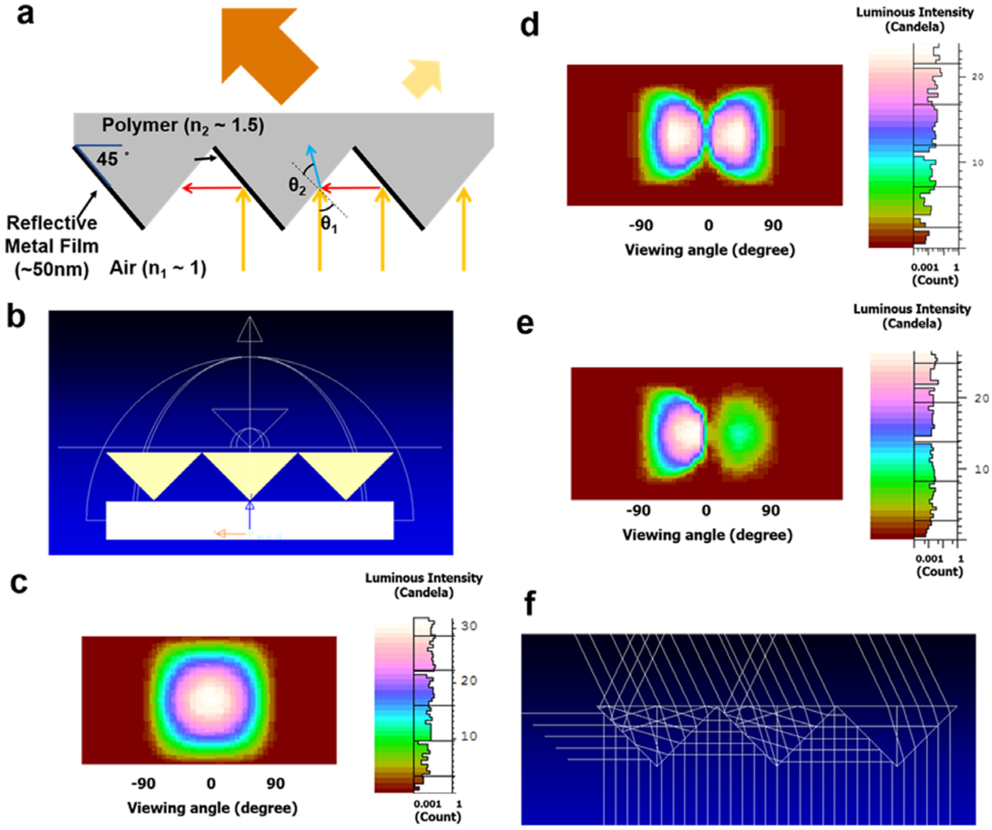

Figure 3. (a) A scheme of the light pathway of incident light through the directionally reflective prism array. (b) The prism arrays design for the optical simulation. Left faces of the prisms are defined as a reflector. The prism sheet is placed between a light source and a detector. Isoluminance contours of the lambertianin light source (c), after penetrating a normal prism array (d) and reflective Janus-faced prism array (e). We note the maximum luminous intensities are different respectively. (f) Light rays traced by the optical simulation.

the isoluminant contours with normal and reflective Janus-faced prism array after the optical simulation. As shown in Figure 3(d), the highest luminance is on the right and the left side symmetrically through normal prism array, which is the same with the experimental data (Figure 2(a)). With the directionally reflective prism array (Figure 3(e)), the left side shows the highest luminance and there is a small portion of leakage of the light to the right direction. Figure 3(f) shows that the reflected rays can be guided to the left direction and there are some strayed rays after multiple reflections on the reflective metal films and the prism surfaces. We note that the maximum luminances are 24 candelas in the normal prism array (Figure 3(d)) and 27 candelas in the reflective prism array, which shows that there is a 12.5% of amplification in the reflective Janus-faced prism array. The scattering effect on the faces of prism arrays due to the surface roughness can be the reason of broad distribution of amplification of experimental data, which is different from the simulation results.

Then, we turn our focus on the utilization of the small portion of the strayed rays to the unwanted direction. The ability of the reflective Janus-faced reflective prism array to disproportionately allocate the incident light intensity suggests its use in the fabrication of unique micro/nanostructures that cannot be achieved by conventional lithographic methods or even with our previous Lucius prism arrays.[16,17] If the light is intensified in a certain direction and the directional light is utilized in patterning a PR, a directionally oriented structure can then be easily fabricated by simple exposure of the resist to the beam through the designed prism array. Directionally oriented micro/nano objects are of great interest due to their unique characteristics such as adhesion hysteresis in gecko-like dry adhesives and unidirectional wetting on angled structures, or pillars.[18-24] More interestingly, We could manipulate the directional structures with controlling UV exposure time. Figures 4(a) and 4(b) are the experimental set-ups used to create directionally oriented micro objects along with the crosslinked PR regions for different exposure times. A Cr pattern with an array of holes on the top of a glass substrate was prepared by wet etching with standard photolithography. A negative photoresist was spin-cast on top of the Cr mask and dried. In the absence of the prism array, up-right pillars were obtained, as expected (Figure 4(c)). Since the exposed part of the negative resist is crosslinked, it becomes insoluble in a developer that removes the rest of uncured resist. In the presence of the single-sided reflective prism sheet, however, slanted coffee-pot-like structures are formed (Figure

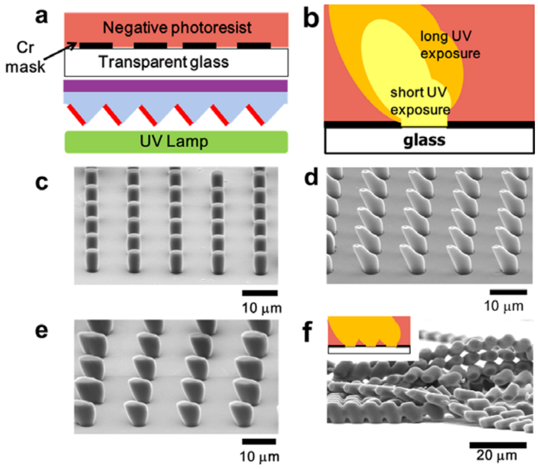

Figure 4. (a) An experimental setup to fabricate directionally oriented structures by the simple UV exposure. (b) A schematic illustration of the areas of the crosslinked negative photoresist (PR) with different exposure times. (c) A SEM image of developed negative PR when the PR is exposed to UV without a prism film. (d) A SEM image of developed negative PR when PR is exposed for 30 s with the directionally reflective prism array. (e) A SEM image of the same PR when the UV exposure time is increased to 60 s with the directionally reflective prism array. (f) Bullet cartridge-belt structures obtained when the spacing between pillars remains relatively narrow.

4(d)), in contrast to the up-right pillars shown in Figure 4(c). The tilted angle of ~23° obtained from the SEM image in Figure 4(d) is consistent with the predictions of the Snell's model. Due to the light intensity distribution in the beam produced through the reflective Janus-faced prism array (see Figure 4(b)), the shape of the feature could also be manipulated. When the exposure time was increased from 30 s to 60 s, for example, spatula-shaped pillars were obtained as shown in Figure 4(e). A longer exposure time causes further crosslinking of the negative PR that would not have been crosslinked in a shorter exposure time, resulting in the change of pillar shape. Shown in Figure 4(f) is a bullet cartridge belt structure obtained when the distance between adjacent pillars is close enough to cause the bonding between the pillar sides. We also note that the features fabricated with photoresist show high resolution compared to our previous results,[11] which is due to the high sensitivity of the photoresist.

Conclusions

In this work, we demonstrated the directional amplification of luminance and the fabrication of complex directional oriented structures by employing the reflective Janus-faced prism array. From the sacrifice of the luminance in an unwanted direction by the reflection, we could enhance the luminance in the desired direction. The directional amplification of light intensity can certainly be utilized in flat panel displays and illumination systems. It can also be utilized in fabricating directional orientation and feature shapes. The unique light intensity distribution in the directed rays can be utilized to manipulate the shape of structures simply by varying the light exposure time as well as the spacing between them.

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