Large-area fabrication of a *Morpho* butterfly-inspired optical diffuser using nanoimprint lithography

Kazuma Yamashita [1], Takuma Hattori [1,2], Yuji Kuwahara [1,2], and Akira Saito [1,2]
[1] Department of Precision Engineering, Osaka University, Suita, Osaka, 565-0871, Japan
[2] RIKEN SPring-8 Center, Sayo-gun, Hyogo, 679-5148, Japan
E-mail: yamashita@ss.prec.eng.osaka-u.ac.jp

To create uniform illumination, optical diffusers are indispensable for various lighting systems such as LED lighting and liquid crystal displays. In addition, their light scattering properties are also utilized in applied research (e.g., daylight harvesting, laser optics, chemical sensors, and medicine [1]). However, owing to the optical inefficiency of multiple scattering and/or surface reliefs vulnerable to contamination, it remains a major challenge for conventional and other novel diffusers to realize high optical performance and anti-fouling properties, both of which are required for ideal optical diffusers [2].

In contrast, the disordered nanostructure of *Morpho* butterflies (Fig. 1a,b) exhibits outstanding light diffusion and superhydrophobic self-cleaning ability (like lotus leaves) simultaneously. Inspired by this nanostructure, we have recently developed a novel diffuser (*Morpho*-type diffuser) with high optical performance and anti-fouling properties [3]. As shown in Figure 1c, the diffuser comprises randomly arranged binary (two-level) nanopatterns on either surface, which result in wide-angle diffraction without forming gratings. Thus, the diffuser can be easily fabricated using nanoimprint lithography, where the binary nanopatterns are first created on silicon molds and then imprinted onto a transparent resin. Among various nanoimprintable materials, we selected polydimethylsiloxane (PDMS) for its hydrophobicity (water contact angle > 90°) to induce the self-cleaning effect. Consequently, a *Morpho*-type diffuser with the high performance summarized in Figure 2 was achieved.

However, the area of the prototype diffuser was only 6×6 mm^2 due to the low throughput of electron-beam lithography (Fig. 3a,b), and therefore we could not perform any practical applications. To address this issue, we have drastically enlarged the mold size up to a full 300 mm wafer by photolithography. Using a KrF stepper (exposure wavelength: 248 nm), the nanopattern with the minimum feature size of 300 nm was successfully fabricated over the entire wafer with continuous stitching (Fig. 3c,d). Finally, the large-area mold was nanoimprinted onto a UV-curable PDMS (KER-4690, Shin-Etsu Chemical) to obtain the large-area diffuser (Fig. 3e,f). The PDMS replica can also be used as the mold of roll-to-roll nanoimprinting, further facilitating its industrialization. Therefore, the presented diffuser has great potential as an innovative optical diffuser for various lighting applications.

References:

[1] a) H. Wachenfelt et al., *J. Daylighting* **2015**, *2*, 21; b) H.-A. Chen et al., *Opt. Express* **2017**, *25*, 18140; c) M. Elsherif et al., *ACS Nano* **2018**, *12*, 2283; d) M. Li et al., *IEEE Trans. Med. Imaging* **2021**, *40*, 346.
[2] a) X. Liu et al., *Opt. Express* **2015**, *23*, 17793; b) G. Liang et al., *Adv. Photonics Res.* **2021**, *2*, 2100185; c) M. Shrestha et al., *ACS Photonics* **2018**, *5*, 3255; d) T. Alqurashi et al., *Nanoscale* **2018**, *10*, 7095.
[3] a) K. Yamashita, A. Saito et al., *Opt. Express* **2021**, *29*, 30927; b) K. Yamashita, A. Saito et al., "Development of a high-performance, anti-fouling optical diffuser inspired by *Morpho* butterfly's nanostructure," *Adv. Opt. Mater.*, accepted.

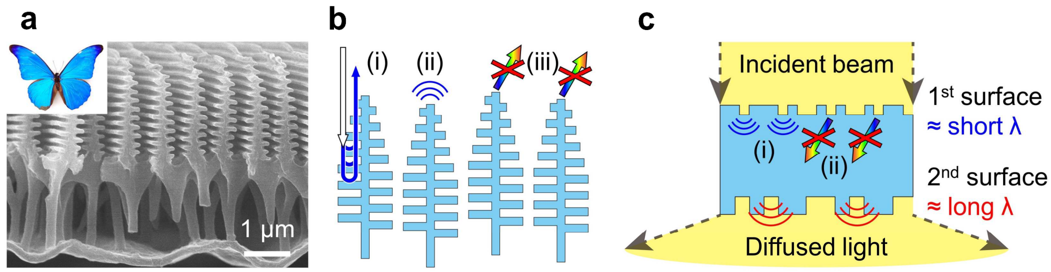

Figure 1. a) Cross-sectional SEM image of the wing scale of a male *Morpho* butterfly (*M. rhetenor*). Inset: photograph of the butterfly. b) Schematic of the *Morpho* butterfly's structural coloration, which exhibits uniform blue color at wide viewing angles. (i) Multilayer interference, (ii) wide-angle diffraction due to a small width, and (iii) anti-grating effect due to a random arrangement. c) Schematic of the *Morpho*-type diffuser. (i) Wide-angle diffraction and (ii) anti-grating effect.

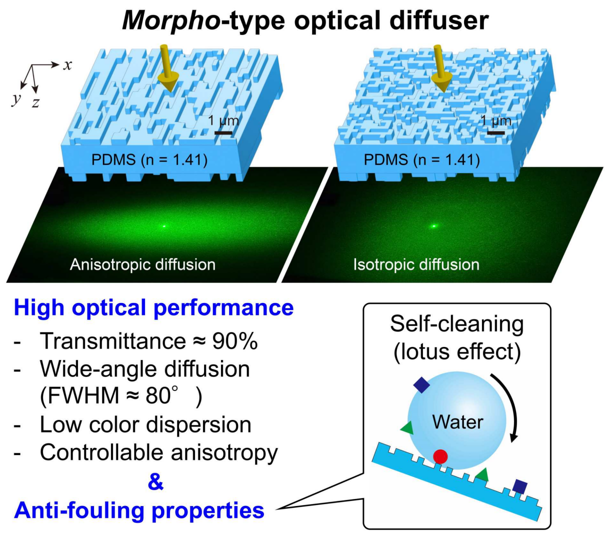

Figure 2. Summary of the performance attained by the *Morpho*-type diffuser.

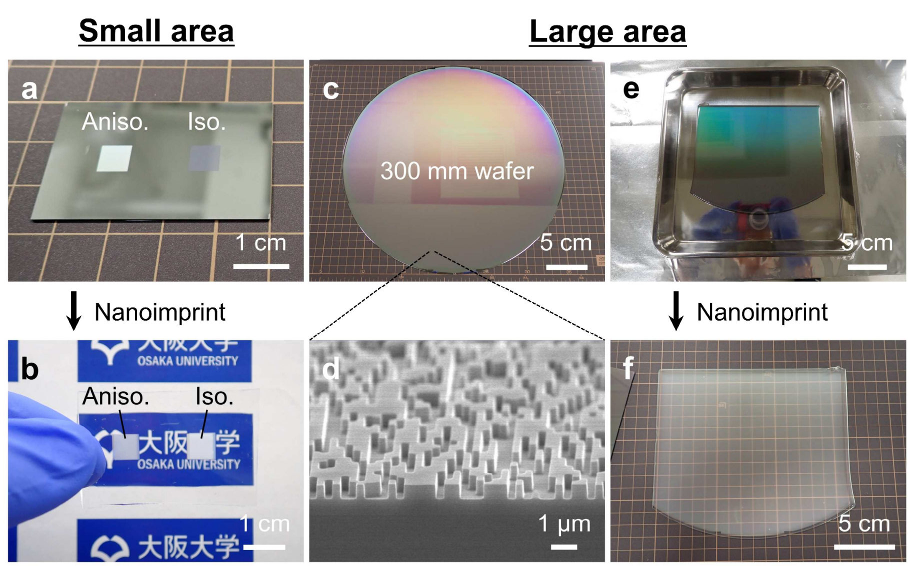

Figure 3. a,b) Small-area mold (patterned area: 6 × 6 mm^2) and the obtained prototype diffuser, respectively. c,d) Large-area mold (patterned area: full 300 mm wafer) and its SEM image, respectively. e,f) Fabrication of the large-area diffuser.