Fabrication of spatially thickness-varying film by grayscale plasma etching

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Spatially thickness-varying film has been widely used in optical devices based on phase and amplitude modulation like color filter [1] and diffraction optical elements [2]. Diverse methods like conventional multi-step lithography, grayscale lithography and grayscale stencil lithography have been proposed to make thin film pattern with varying thickness.

Herein, an alternative method named grayscale plasma etching is demonstrated to realize the fabrication of spatially thickness-varying film. A patterned nickel film is used as the shadow mask in plasma etching and the fabrication schematic is shown in Figure 1. The shadow mask carries dense holes with filling ratios spatially modulated. When placed above the sample with a proper separation, the openings on the mask will modify the plasma etching rate according to the gap *d* and the filling ratio of the pattern on nickel film mask.

A hybrid method as shown in Figure 2 is adopted to fabricate the patterned nickel film. Interference lithography and secondary grayscale exposure are firstly used to define required patterns on photoresist. And then electroplating is employed to fabricate the nickel film. Finally, the nickel film is peeled off from the ITO substrate. The fabricated nickel mask is shown in Figure 3. The periods of the pattern is 1.5 μm and the diameter of the nanohole can be varied spatially according to the exposure intensity patterns.

To demonstrate the feasibility of the proposed strategy, a spacer with different thickness is utilized in the plasma etching. The etching results with $d = 0$ and 0.5 mm are shown in Figure 4. With $d = 0$ mm, the diffraction of the pattern can be seen, which indicates the periodic pattern is fabricated on the sample. With $d =$ 0.5 mm, the diffraction disappears and the color of the pattern become uniform. This implies that the etching patterns of the holes overlap with each other because the plasma species spread laterally after passing through the nanoholes and a planar etching is realized.

To achieve materials etching with spatial thickness variation, a mask with spatially filling-ratio-varying pattern should be prepared. And the spread function of the plasma species after passing through the nanohole can be derived. Besides, this method can be applied to customize thickness varying layer, showing the potential to fabricate high-performance planar optical devices like color filter array with high efficiency, precise thickness tunability and low cost.

[1] X. Li, Z. J. Tan, and N. X. Fang, *Optica* **7**(9), 1154-1161 (2020)
[2] S. Colburn, A. Zhan, and A. Majumdar. *Sci. Rep.* **7**, 40174 (2017).

Figure 1: The shadow mask plasma etching schematic.

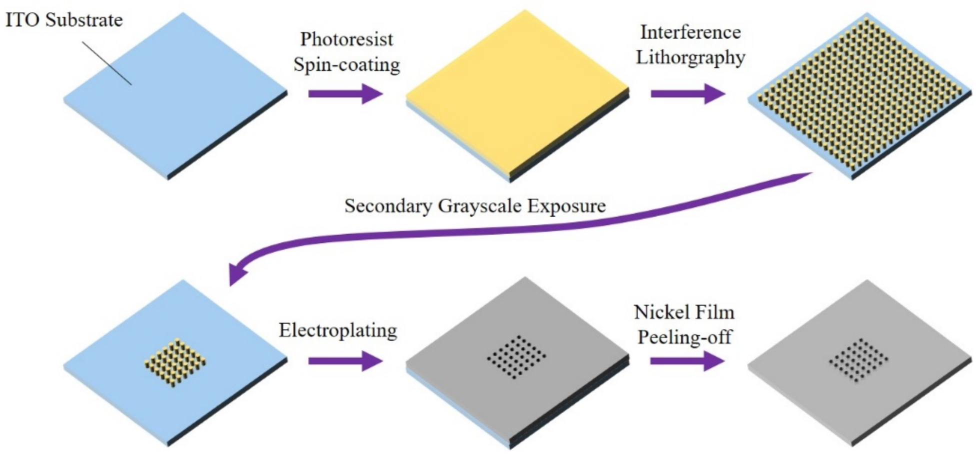

Figure 2: The fabricating procedure of the patterned nickel film.

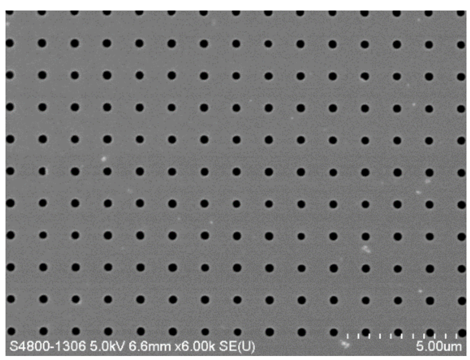

Figure 3: SEM image of the nickel mask.

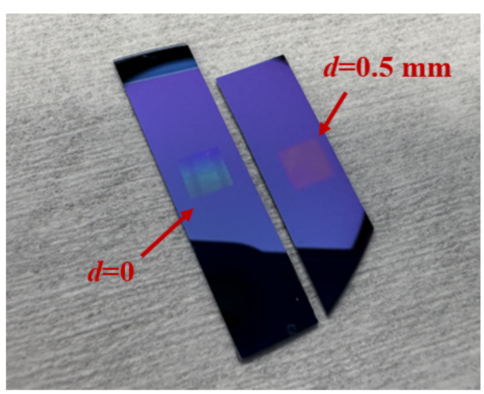

Figure 4: Etching results with $d = 0$ and 0.5 mm.