Additive diffractive optical elements fabrication by PECVD deposition of SiO2 and lift-off process

Hadi Amata[a], Qiang Fu[a], and Wolfgang Heidrich[a]

[a]King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

ABSTRACT

Diffractive optical elements (DOEs) gradually start replacing traditional refractive optics in many applications. The growing interest in DOEs is mainly because of their flexibility in light manipulation with a small form factor and their ability to combine simultaneously optical and computational functions into a single part by applying the software-hardware co-design approach. Two main methods are widely used to fabricate DOEs. The first method is the etched-based method that combines photolithography and reactive-ion etching (RIE). The second method is additive fabrication, which combines metal deposition and nanoimprinting (NIL). Both methods have many drawbacks. The RIE methods suffer from issues like lags in the etched depth when the feature sizes differ in the same pattern (RIE lags), high surface roughness, and aspect ratio-dependent etching rate. The second method could produce high-resolution micro-optics. However, the technique could suffer from poor adhesion of the patterns with the substrate and poor uniformity across large areas. Here we propose a new way to fabricate multi-level DOEs by directly growing an optically transparent material on a glass substrate. The method combines the deposition of Silicon dioxide (SiO2) by Plasma-enhanced chemical vapor deposition technique (PECVD) and bi-layer lift-off. We provide evidence of the effectiveness of the fabrication method by comparing a 16-level Fresnel lens fabricated by the RIE method with another lens fabricated by the proposed method. The characterization results show that with the proposed method, the surface roughness is lower, and the depth is uniform. Furthermore, the optical test shows a reduced haze effect.

Keywords: Additive lithography, bi-layer lift-off, PECVD deposition, Multi-level DOEs

1. INTRODUCTION

DOEs use diffraction patterns instead of traditional refractive optics, which rely on light bending through lenses or prisms to achieve their desired effects. This makes them especially useful in applications where conventional optics are limited by size or complexity. DOEs are designed to control the phase and amplitude of light waves, which allows them to perform a variety of functions, including optical and lensless imaging, and allow to build of a computational monocular camera ,[1–4] wavefront sensing,[5] etc. Multi-level DOEs are typically manufactured through several iterations of basic photolithography and reactive-ion etching (RIE) steps. Their ability to achieve high efficiency and precision in optical performance while remaining compact and lightweight is an essential advantage .[6–8] These kinds of applications require DOEs that are versatile, high diffraction efficient, and simple to fabricate.

The most common DOEs fabrication methods involve several photolithography masking and RIE .[6] Unfortunately, etching methods suffer from high surface roughness, RIE lag, aspect ratio-dependent etching (ARDE), and other artifacts such trenching, faceting, etc. [9,10]

To overcome these issues, researchers started to explore additive lithography techniques to build a multi-level DOE, including the photoresist additive lithography method.[11,12] However, this technique still requires an etching step to transfer the pattern onto the substrate to build the required DOE. Recently, a promising etch-free additive lithographic fabrication technique to build DOEs has been demonstrated.[13,14] The method is based on the additive fabrication to directly fabricate muli-level DOEs by depositing Chromium (Cr) or Aluminum (Al) onto fused silica (FS) substrates by sputtering followed by lif-toff to create a master stamp (metal stamp) and

Further author information: (Send correspondence to H.A.)
H.A.: hadi.amata@kaust.edu.sa, Q.F.: Qiang.Fu@kaust.edu.sa, W.H.: wolfgang.heidrich@kaust.edu.sa

then transferring the final patterns to proper transparent substrates by Nanoimprint lithography (NIL), this method shows less topology artifact compared to the soft lithography.[15] However, the lack of flexibility, poor adhesion of the patterns to the substrate, costs, limited versatility, and poor uniformity throughout large areas remain major drawbacks of these NIL-based methods .[16–18]

This work proposes and demonstrates alternate etch-free and NIL-free additive DOE fabrication processes to address the abovementioned problems. We propose a new additive fabrication method of fabricating the DOE directly by growing an optically transparent material on a transparent substrate. The deposited material should have the same optical characteristics as the substrate. A silicon dioxide material is directly deposited onto a fused silica substrate by the Plasma-enhanced chemical vapor deposition (PECVD) [19] method followed by a bi-layer liftoff. [20,21]We can fabricate a 16-level DOE with four iterations of the liftoff process by using binarization advantage. We can thoroughly eliminate the etching and nanoimprinting steps with the proposed additive fabrication method. The deposition rate by PECVD is well-controlled and uniform, allowing perfect depth control for large and small feature sizes co-existing in the same wafer. Low surface roughness is demonstrated compared with the plasma etching method. Optical tests also confirmed the tremendous impact of these improvements made by our process on the imaging quality of the 16-level Fresnel lens fabricated by the proposed method.

2. FABRICATION DETAILS

To fabricate the Fresnel lens, we employ an additive lithographic fabrication workflow similar to the fabrication of reflective DOEs .[14] Compared with reflective DOEs, we kept all the lithography steps. We replaced only the deposited reflective material with an optically transparent material. Therefore, with the lithography and the PECVD method to do the silicon dioxide (SiO2) deposition, we can create the microstructure in an additive, etch-free and NIL-free way. To make 2^N level structures, the basic deposition-liftoff cycle can be repeated N times. In Fig. 1, we show two cycles of the fabrication process.

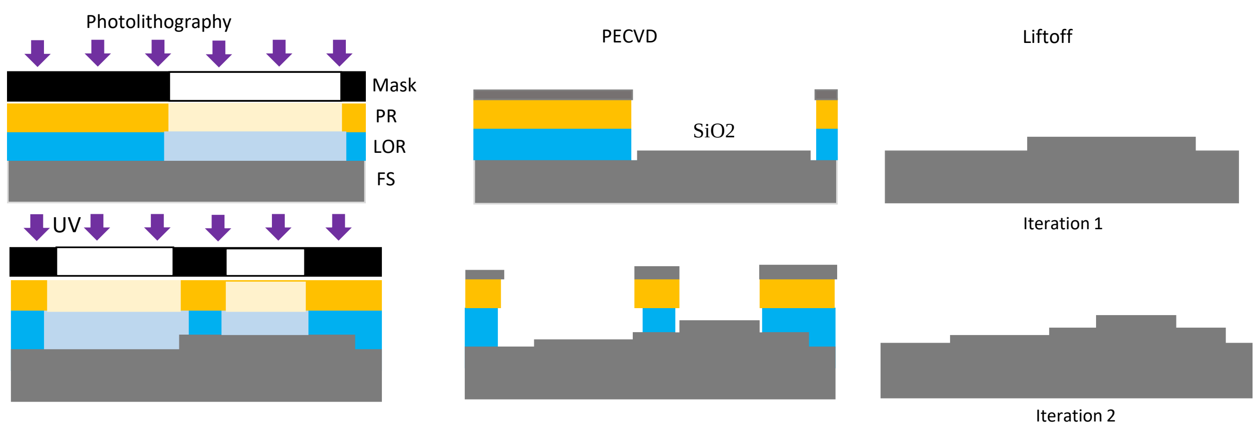

Figure 1. ***Fabrication of 16 level frenel lens.*** Each iteration creates 2-level microstructures on the previous profile by applying lift-off lithography followed by SiO2 deposition. By repeating the fabrication cycle 4 times, one can obtain 16 levels fresnel lens. PR: photoresist. LOR: lift-off resists. SiO2: Silicon dioxide. FS: fused silica. UV: ultra violet.

3. TEST RESULTS

This section shows several experimental results for a designed Fresnel lens with a focal lens of 100 mm.

3.1 The Fresnel lens phase function

We apply the above fabrication workflow to fabricate a Fresnel lens with a focal lens of 100 mm. The Fresnel lens phase function is presented in Fig. 2. Similar to the work done in the previous papers ,[13,14] We use a 16-level approximation for the continuous phase and generate four fabrication masks for each level by slicing the phase function by a factor of 1/2 each time. The Fresnel lens phase consists of central rings with large feature sizes. The size of the ring's features decreases linearly from the center to the edge. Obviously, if we want a lens with better performance, the edges' rings must have the highest spatial resolution, whereas the large rings must have large flat regions. These features should be the same thickness in the final sample, with as little surface roughness as possible. This is especially challenging for conventional RIE and NIL fabrication methods, but it is achievable with the proposed additive fabrication.

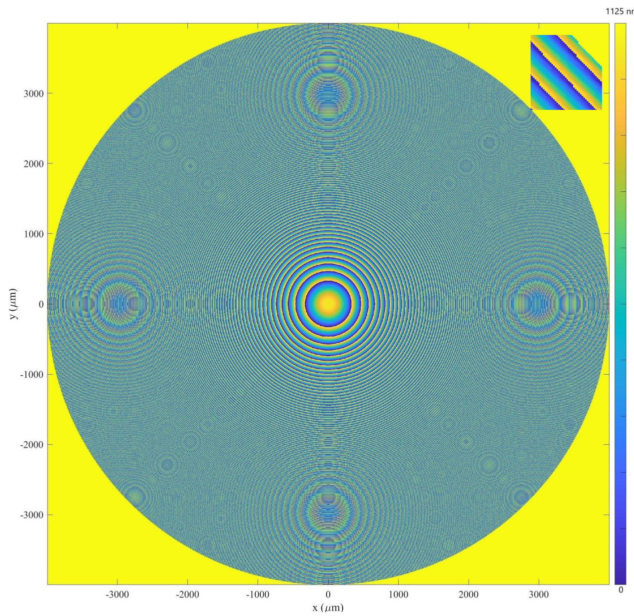

Figure 2. The designed Fresnel lens; Discretized 16-level height profile.

3.2 SEM measurements

We fabricated two DOEs, the first with the conventional RIE method and the second with the proposed additive method. And by using the Nova NanoSEM630 SEM machine, we made SEM measurements of the Etched Fused Silica wafer and the deposited SiO2 layer. The results are shown in Fig. 3.

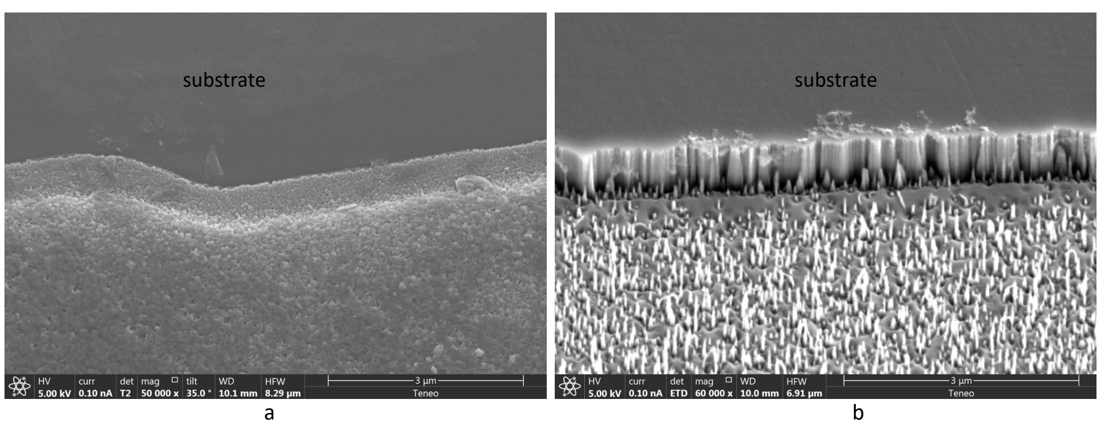

Figure 3. SEM characterization using Nova NanoSEM630 machine: a- additive sample, b-RIE sample.

The upper part of the SEM images shows the substrate surface roughness, and the lower side shows the etched part for the RIE sample and the deposited SiO2 for the additive sample. The results clearly show that the surface of the additive DOE is significantly smoother than the surface of the etching DOE.

3.3 AFM measurements

We used a Bruker Dimension Icon Atomic Force Microscope System to study the depth uniformity across the DOE for the samples described in the section above. We made a 20um scan in the center of the DOE where the DOEs features size is larger than 15 um, and a 20um scan in the edges of the DOEs where the DOEs features size is less than 5um. The obtained results are shown in Fig. 4.

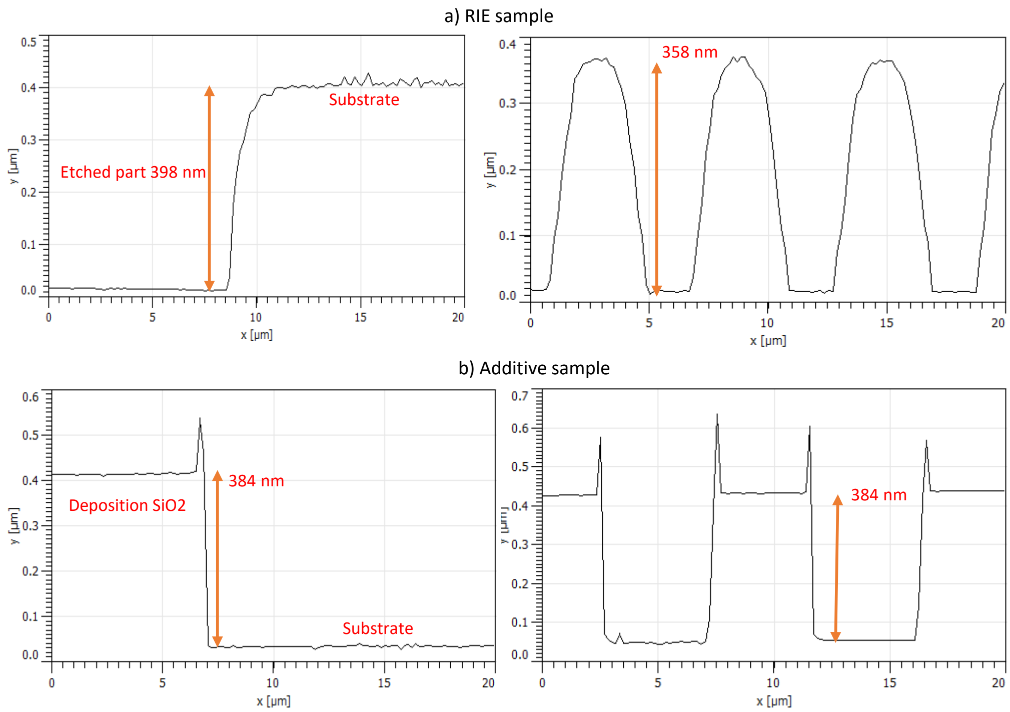

Figure 4. AFM characterization using Bruker Dimension Icon Atomic Force Microscope System. The X-axis represents the DOE feature size, and the y-axis represents the DOE depth.

Fig. 4-a represents the results from the DOE fabricated by RIE. The RIE lags are obvious because the difference in the depth between the center of DOE and its edge is 40 nm. This is not the case for the results obtained from the additive DOE Fig. 4-b, representing a perfect depth uniformity.

3.4 Optical measurements

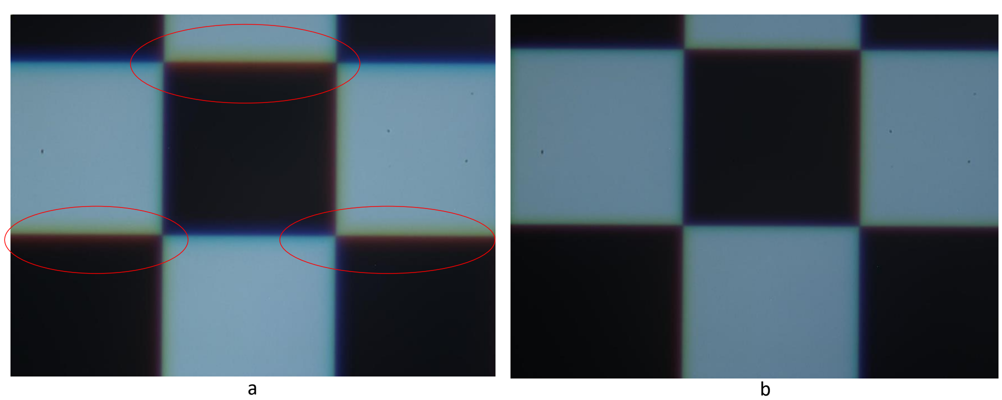

Figure 5. Optical characterization: a-Image capture with the additive lens, b-image captured with RIE lens .

The SEM and AFM characterization measurements presented in the above sections demonstrated that the proposed additive DOE fabrication method is capable of eliminating the two main issues of the conventional RIE method. We build an imaging prototype using off-the-shelf Thorlabs lens tubes, 3D custom DOE mounts, and a FLIR Grasshopper3 image sensor to measure the impact on the imaging quality of the lens fabricated by the proposed method. The results presented in Fig. 5 show a reduced haze effect for the additive lens compared to the lens fabrication by the conventional RIE method. The reduced haze comes from the smoothness of the microsurface fabricated by SiO2 deposition which gives the additive DOE a higher diffraction efficiency.

4. DISCUSSION

The results demonstrate that the proposed additive lithographic fabrication can produce high-quality DOEs with very low surface roughness and good depth uniformity across a large wafer area. Using an imaging prototype, a 16-level Fresnel lens verifies the optical performance with less haze in the captured images. There are a few defects in the current DOEs made by our method. The PECVD deposition of SiO2 is done at a low temperature of 140 degrees Celsius because the transition temperature of the lift-off process is 200 degrees, and it's safer to keep the critical dimensions (CDs) of the DOE unchanged to do the PECVD deposition at temperatures less than 150 degrees Celsius. This might limit the amorphous statute of the deposited material. This is visible in Fig. 3-a, where we can see an aggregation of SiO2 particles. Further investigation is needed using the X-ray diffraction method (XRD analysis) to confirm that deposited SiO2 material is amorphous and consists of nanoparticles of SiO2 material with the sizes of a few nanometers without a significant impact on DOE optical performances. We also looking for a possible solution to mitigate this issue by using, for example, a Thermostable photo resists like SX ARP 3500/8 photoresist as the top layer of the lift-off process. Second, some nanometer-thin spikes are present around the edges of Fig. 4-b, especially as the deposited target height increases. This effect is feature size-specific rather than wafer-wide. The possible reason is that the lift-off process may have left a thin SiO2 film on the sidewalls of the PR because the thickness difference between LOR and SiO2 is not significant enough for the developer to enter. The spikes are too thin and fragile and appear only when the feature sizes of the pattern are less than 5um. To remove them, we are exploring some chemical and mechanical solutions, like immersing the sample in HF solution for a short while or mechanically breaking off the spikes by pressing the DOE into a sheet of soft material.

5. CONCLUSION

This paper demonstrates a new way to fabricate multi-level diffractive optical elements through the direct growth of optically transparent material on a glass substrate. The proposed fabrication used the PECVD deposition method in conjunction with bi-layer lift-off lithography. The technique is etch-free and doesn't require a nanoimprint step. A 16-level Fresnel lens is fabricated by this method. Low surface roughness, better depth uniformity, and better optical performances than the etch-based method are demonstrated. These findings highlight the additive method's potential as an alternative to the traditional RIE method for fabricating various micro-optic types.

ACKNOWLEDGMENTS

This work was partly supported by King Abdullah University of Science and Technology (KAUST) individual baseline funding and KAUST Visual Computing Center operational funding. The fabrication was done in the Nanofabrication Corlabs at KAUST.

REFERENCES

[1] Peng, Y., Fu, Q., Amata, H., Su, S., Heide, F., and Heidrich, W., "Computational imaging using lightweight diffractive-refractive optics," *Opt. Express.* **23**(24), 31393–31407 (2015).

[2] Peng, Y., Fu, Q., Heide, F., and Heidrich, W., "The diffractive achromat full spectrum computational imaging with diffractive optics," in [*SIGGRAPH ASIA 2016 Virtual Reality meets Physical Reality: Modelling and Simulating Virtual Humans and Environments*], 4, ACM (2016).

[3] Fu, Q., Yan, D.-M., and Heidrich, W., "Diffractive lensless imaging with optimized Voronoi-Fresnel phase," *Optics Express* **30**(25), 45807–45823 (2022).

[4] Shi, Z., Bahat, Y., Baek, S.-H., Fu, Q., Amata, H., Li, X., Chakravarthula, P., Heidrich, W., and Heide, F., "Seeing through obstructions with diffractive cloaking," *ACM Trans. Graph.* **41**(4) (2022).

[5] Cagigal, M. P. and Valle, P. J., "Wavefront sensing using diffractive elements," *Opt. Lett.* **37**(18), 3813–3815 (2012).

[6] O'Shea, D. C., Suleski, T. J., Kathman, A. D., and Prather, D. W., [*Diffractive optics: design, fabrication, and test*], vol. 62, SPIE Press Bellingham, WA (2004).

[7] Fischer, R. E., Tadic-Galeb, B., Yoder, P. R., Galeb, R., Kress, B. C., McClain, S. C., Baur, T., Plympton, R., Wiederhold, B., and J, B. G. A., [*Optical system design*], 259–318, Citeseer (2000).

[8] Cox, J. A., Werner, T. R., Lee, J. C., Nelson, S. A., Fritz, B. S., and Bergstrom, J. W., "Diffraction efficiency of binary optical elements," in [*Computer and Optically Formed Holographic Optics*], **1211**, 116–124, International Society for Optics and Photonics (1990).

[9] Franssila, S. and Sainiemi, L., [*Reactive Ion Etching (RIE)*], 1–13, Springer US, Boston, MA (2013).

[10] Laermer, F., Franssila, S., Sainiemi, L., and Kolari, K., "Chapter 21 - deep reactive ion etching," in [*Handbook of Silicon Based MEMS Materials and Technologies (Second Edition)*], Tilli, M., Motooka, T., Airaksinen, V.-M., Franssila, S., Paulasto-Kröckel, M., and Lindroos, V., eds., *Micro and Nano Technologies*, 444–469, William Andrew Publishing, Boston (2015).

[11] Pitchumani, M., Hockel, H., Mohammed, W., and Johnson, E. G., "Additive lithography for fabrication of diffractive optics," *Appl. Opt.* **41**(29), 6176–6181 (2002).

[12] Pitchumani, M., Hockel, H., Brown, J., Mohammed, W. S., and Johnson, E. G., "Additive lithography for refractive micro-optics," in [*Micromachining Technology for Micro-Optics and Nano-Optics*], **4984**, 1–9, International Society for Optics and Photonics (2003).

[13] Fu, Q., Amata, H., and Heidrich, W., "Etch-free additive lithographic fabrication methods for reflective and transmissive micro-optics," *Optics Express* **29**(22), 36886–36899 (2021).

[14] Fu, Q., Amata, H., Gerard, B., , Christian, M., and Heidrich, W., "Additive lithographic fabrication of a Tilt-Gaussian-Vortex mask for focal plane wavefront sensing," in [*OptiFAB 2021*], **11889**, 1188911:1–9, International Society for Optics and Photonics (2021).

[15] Qin, D., Xia, Y., and Whitesides, G. M., "Soft lithography for micro-and nanoscale patterning," *NatProtoc* **5**(3), 491–502 (2010).

[16] Dongxu Wu, N. S. R. and Luo, X., "Nanoimprint lithography - the past, the present and the future," *Current Nanoscience* **12**, 712–724 (2006).

[17] Guo, L. J., "Nanoimprint lithography: Methods and material requirements," *Advanced Materials* **19**(4), 495–513 (2007).

[18] Stephen Y.Chou, P. R. K. and Renstrom, P. J., "Imprint lithography with 25-nanometer resolution," *Science* **272**(85-87) (1996).

[19] J. Batey, E. T., "Nlow-temperature deposition of high-quality silicon dioxide by plasma-enhanced chemical vapor deposition," *Journal of Applied Physics* **60**, 3136–3145 (1986).

[20] Popovich, L. L., Gehoski, K. A., Mancini, D. P., and Resnick, D. J., "Bilayer and trilayer lift-off processing for i-line and duv lithography," in [*Optical Microlithography XV*], **4691**, 899–906, International Society for Optics and Photonics (2002).

[21] Wilson, T. E., Korolev, K. A., and Crow, N. A., "Bilayer lift-off process for aluminum metallization," *Journal of Micro/Nanolithography, MEMS, and MOEMS* **14**(1), 014501 (2015).