

Defect characterization, advanced etching techniques, and large field-of-view imaging for metalenses

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2025

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This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

Chenxu Zhu was the sole author for Chapters 1, 2, and 5, which were written under the supervision of Dr. Bo Cui and Dr. Dayan Ban, and were not written for publication.

This thesis consists of one manuscript intended for publication and one that has been published. Exceptions to sole authorship of material are as follows:

Research presented in Chapter 3:

Chenxu Zhu conducted this research under the supervision of Dr. Bo Cui and Dr Cheng Zhang. I was responsible for the experimental planning, device simulation, and sample fabrication. Zhenyu Xing contributed to the sample measurement and analysis. Aixi Pan and Jian Yin assisted in the analysis and manuscript reviewing. This work is intended for publication, and Chenxu Zhu is the first author.

Research presented in Chapter 4:

Zhu, X., Wang, Z., Zhu, C., Shen, J., Shokouhi, B., Ekinci, H., Cui, B. (2024). Multi-step plasma etching of high aspect ratio silicon nanostructures for metalens fabrication. Journal of Vacuum Science & Technology B, 42 (3), 032203.

This chapter discusses the research conducted by Dr. Xiaoli Zhu under the supervision of Dr. Bo Cui. Xiaoli Zhu initiated the project, designed the entire experiment, and wrote the manuscript. Zihao Wang and Chenxu Zhu contributed equally to the fabrication, data collection, and sample characterization. Jiashi Shen assisted with sample characterization. Babak Shokoushi provided the funding. Huseyin Ekinci aided in reviewing the manuscript.

Other published works beyond the scope of this thesis:

- Zhu, C.**, Pan, A., Zhu, X., Zheng, S., Cui, B. (2024). Edge lithography based on aluminum dry etching. *Micro and Nano Engineering*, 22, 100233.
- Zhu, C.**, Ekinci, H., Pan, A., Cui, B., Zhu, X. (2024). Electron beam lithography on nonplanar and irregular surfaces. *Microsystems and Nanoengineering*, 10(1), 52.
- Jin, T., **Zhu, C.**, Qiu, Y., Zhao, X., Zhong, Q., Dong, Y., Song, Q., Bo, C., Zheng, S., Hu, T. (2024). Metasurface-driven dots projection based on generalized Rayleigh-Sommerfeld diffraction theory. *Chinese Optics Letters*, 22(10), 103601.
- Pan, A., **Zhu, C.**, Yan, Z., Zhu, X., Liu, Z., Cui, B. (2024). Fabrication of the highly ordered silicon nanocone array with sub-5 nm tip apex by tapered silicon oxide mask. *IEEE Transactions on Semiconductor Manufacturing*, 37(2).
- Wu, H., Pan, A., **Zhu, C.**, Cui, B. (2024). Fabrication of slanted gratings by using glancing angle deposition. *Journal of Vacuum Science & Technology B*, 42(2), 023002.
- Huang, Y., Xiong, M., Zhang, P., **Zhu, C.**, Cui, B., Zhao, X., ... & Hu, T. (2024). Broadband Achromatic Metalens with Enhanced Field of View for Thermal Image. *Journal of Lightwave Technology*.
- Aydinoglu, F., Pan, A., **Zhu, C.**, Cui, B. (2020). Effect of oxygen plasma cleaning on the nonswitching pseudo-Bosch etching of high aspect ratio silicon pillars. *Journal of Vacuum Science & Technology B*, 012804.

Abstract

Metalenses, made of nanostructures, have attracted significant interest for their ability to overcome the limitations of traditional lenses. This thesis provides a thorough study on the design, fabrication, and characterization of high-performance metalenses using metasurface technology. It underscores the interactions among fabrication imperfections, advanced nanofabrication techniques, and imaging performance across a large field of view (FOV).

Defects in metalenses introduced during fabrication can significantly affect their optical performance. Chapter 3 carried out a unique experimental analysis using real-fabricated devices to investigate the impact of different defects, including inclined sidewall angle, uniform critical dimension bias, non-uniform bias due to the proximity effect, and the notching effect in etching, on parameters such as focal spot intensity, focal length, and Strehl ratio (SR). Our research indicates a 47% decrease in intensity when the sidewall is positively tapered by 4° , a 15% intensity reduction with a 30 nm deviation in structure size, minimal intensity and focusing quality deterioration with the non-uniform bias, and a 13% intensity decrease along with a significant drop in focusing quality when the notching effect occurs. Our study provides critical insights into the tolerances required for optimal metalens performance and offers recommendations for time and cost savings.

Chapter 4 introduces an innovative etching technique that utilizes a three-step $\text{C}_4\text{F}_8/\text{SF}_6$ plasma etching process with varying gas ratios at different depths. By maintaining the plasma after each step, this continuous three-step process offers enhanced flexibility for tuning the etching of high aspect ratio (HAR) nanostructures, resulting in smooth and vertical profiles. By using the optimal gas ratio, metalens nanostructures with diameters

of 71 nm and heights of 1 μm were successfully created, with feature size variation kept to less than 10 nm. This proposed continuous multi-step approach significantly improves the controllability of silicon nanopillar etching, which is crucial for achieving precise phase control and effectively manipulating light in metalens applications.

Building on these advancements, Chapter 5 details the design and fabrication of a single-layer metalens that achieves a broad FOV of 120° at a near-infrared wavelength of 940 nm. The metalens features a simple structure consisting of a metallic aperture paired with a single-layer metasurface. To optimize the phase profile of the metalens, a ray-tracing algorithm was utilized. The resulting enhanced metalens demonstrates commendable focusing efficiency (35-61%) and diffraction-limited imaging ($\text{SR} > 0.8$), positioning it as a promising candidate for applications in imaging, sensing, and integrated photonic systems.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisors, Prof. Bo Cui and Prof. Dayan Ban, for their invaluable guidance, unwavering support, and patient mentorship throughout my doctoral research. From the initial discussions of research direction to the final stages of writing, they provided insights that shaped both my scientific understanding and my approach to problem-solving. Their encouragement during challenging moments and their constructive feedback on experiments, simulations, and manuscript drafts have been essential to the completion of this thesis. I am particularly thankful for the freedom they provided to explore innovative ideas in metasurface fabrication.

I want to extend my gratitude to my committee members, Prof. Guo-Xing Miao, Prof. Eihab Abdel-Rahman, Prof. William Wong, and Prof. Wai Tung Ng, for dedicating their time to reviewing my thesis and providing valuable feedback. Your critical insights and thoughtful suggestions not only helped clarify complex aspects of the research but also provided a new perspective. The encouragement and guidance from each of you have been instrumental in helping me navigate the complexities of my study, fostering a deeper and more nuanced understanding of the subject matter.

I would also like to thank the members of our research group—Dr. Xiaoli Zhu, Dr. Ferhat Aydinoglu, Dr. Ripon Kumar Dey, Dr. Medhat Samaan, Dr. Mohammad Soltani, Dr. Navid MS Jahed, Dr. Huseyin Ekinci, Dr. Zheng Yan, Dr. Farheen Aurangzeb, Dr. Jian Yin, Dr. Zihao Wang, Dr. Wenhan Hu—for many stimulating discussions, technical assistance, and moral support. Beyond the laboratory, our weekly group meetings and informal brainstorming sessions kept me motivated.

I am deeply indebted to my family for their unconditional love and encouragement. To my parents, Jiang Zhu and Guang Yu: thank you for instilling in me a passion for learning, for believing in my abilities even when I doubted myself, and for making countless sacrifices to ensure I had the opportunity to pursue graduate studies. Your confidence in me has been a foundation that sustained my efforts during long nights of writing and experimentation.

Finally, I would like to acknowledge the broader community at the University of Waterloo: the administrative staff, the cleanroom coordinators, and the technical teams in the nanofabrication and characterization facilities. Without their efficient management of equipment, training sessions, and access protocols, this work would not have been possible.

To all of you—my supervisors, group members, family, and the many friends and colleagues who have shared knowledge, encouragement, and laughter—I thank you. This thesis stands on the collective effort, patience, and goodwill of everyone who contributed, in big and small ways, to my doctoral journey.

Dedication

For my family.

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List of Abbreviations

ALD	Atomic layer deposition
Au	Gold
a-Si	Amorphous silicon
C ₄ F ₈	Octafluorocyclobutane
CD	Critical dimension
Cr	Chromium
Cr ₂ O ₃	Chromium oxide
CVD	Chemical vapor deposition
DI water	Deionized water
DRIE	Deep reactive ion etching
DUV	Deep ultraviolet
EBL	Electron beam lithography
E-beam	Electron beam
FDTD	Finite-different time-domain
FOV	Field of view
GaN	Gallium nitride
HfO ₂	Hafnium dioxide
HAR	High aspect ratio
ICP	Inductively coupled plasma
IPA	Isopropanol
IDA	Ion distribution angle
IBE	Ion beam etching
LPCVD	Low-pressure chemical vapor deposition
MTF	Modulation transfer function
NA	Numerical aperture

NIL	Nanoimprint
PEC	Proximity effect correction
PECVD	Plasma-enhanced chemical vapor deposition
PVD	Physical vapor deposition
RF	Radio frequency
RIE	Reactive ion etching
SA	Sidewall angle
SEM	Scanning electron microscope
SF ₆	Sulfur hexafluoride
Si	Silicon
Si ₃ N ₄	Silicon nitride
SiO ₂	Silicon dioxide
SR	Strehl ratio
TiO ₂	Titanium dioxide
UV	Ultraviolet

Chapter 1: Introduction to metasurfaces and metalenses

This chapter introduces the concept of metasurfaces, primarily focusing on introducing metalenses. It provides an overview of their principles, functionalities, and applications.

1.1 What is metasurfaces and metalenses

Metasurfaces are two-dimensional arrays of subwavelength artificial structures engineered to manipulate light at the nanoscale. Unlike traditional optical components that rely on gradual phase accumulation through bulky materials, metasurfaces create abrupt changes in phase, amplitude, or polarization at a single interface. This fundamental distinction is achieved through the precise design of nanostructures, often referred to as meta-atoms, which interact with incident electromagnetic waves in a highly controlled manner. The design of these meta-atoms—encompassing their shape, size, orientation, and spatial arrangement—enables precise control over various properties of light. By customizing these parameters, metasurfaces can regulate not only the phase but also the amplitude and polarization of incoming light. Typically constructed from metals or dielectric materials, these structures provide a significant reduction in size and complexity compared to traditional optical devices, while simultaneously offering enhanced functionality. Given these benefits, metasurfaces have quickly emerged as pivotal technology in contemporary photonics. Their capacity to finely control light has resulted in various applications, such as metalenses that concentrate light with minimal distortions, sophisticated holographic displays, self-accelerating beam generators, and vortex beam generators.

Metalens serves as a significant application of metasurfaces, crucial for focusing light

in fields such as imaging, energy harvesting, and spectroscopy. Conventional lens designs often employ a convex or concave shape to focus or expand the incident beam. However, it is common to encounter barrel and pincushion distortion at the image corners. Correcting lens aberrations typically involves the creation of bespoke lenses or multiple optical components, which can augment the device's weight and size. In addition, in cases where a device requires a modification in the focal position or a beam is displaced, it becomes crucial to shift the lens stacks, which can ultimately lead to increased instability. Unlike traditional optical lenses, meta-atoms can generate abrupt local phase changes, which makes metalenses ultrathin, ultralight, and compact. Nowadays, they can be designed to perform various functions, including high numerical aperture^{1,2}, achromatic lens^{3,4}, and tunability^{5,6}, which are all highly beneficial in various application scenarios.

1.2 Principles of Metasurface

Metasurfaces are flat surfaces consisting of artificial atoms that manipulate the shape of the wavefront according to the generalized Snell's law^{7,8}. Rather than relying on propagation effects, metasurfaces utilize abrupt alterations in optical properties that are achieved through careful tuning of both materials and parameters within individual unit cells, including metallic (plasmonic) or dielectric nanostructures.

1.2.1 Generalized Snell's Law

The shaping of wavefronts in traditional optical devices like lenses or gratings is due to the gradual phase accumulation along the optical path, as described by the Law of Refraction and Reflection or Snell's Law

$$n_i \sin \theta_i - n_t \sin \theta_t = 0 \quad (1)$$

Where n_i and n_t are refractive indexes of two media, and θ_i and θ_t are angles of incident light and refraction.

In 2011, Dr. Capasso demonstrated groundbreaking research on metasurfaces that employ metamaterials to manipulate the direction of light in unconventional ways, as depicted in Figure 1.1⁷. This led to several remarkable optical phenomena, such as negative refraction, subwavelength focusing, and cloaking^{9,10}, which the Generalized Snell's Law explained.

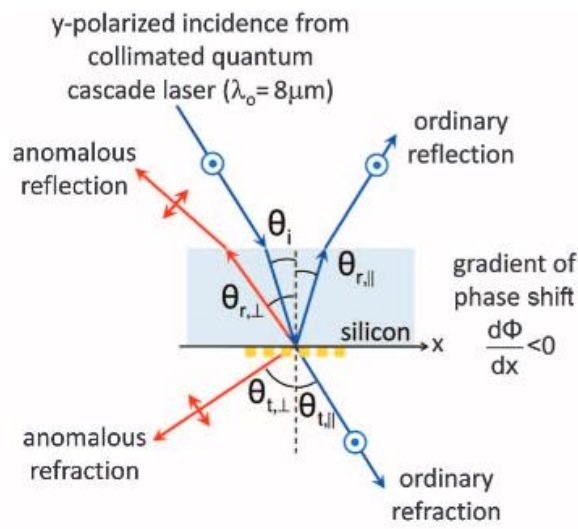


Figure 1.1. The schematic of different types of reflection and refraction obtained by a metalens⁷.

Using Figure 1.2⁷, we can derive the generalized Snell's Law, which allows for a new level of control over wavefronts. This is achieved by introducing phase shifts, or phase discontinuities, along the optical path at a scale comparable to the wavelength of light. The propagation of light is governed by Fermat's principle, which states that the path taken by a ray of light between two points is the one with the least optical path. When considering an incident plane wave at angle θ_i and assuming that the distance between two rays is extremely small (dx), Fermat's principle dictates that the phase difference between them will be zero, so we have:

$$\left[\frac{2\pi}{\lambda} * n_i \sin \theta_i * dx + \Phi + d\Phi \right] - \left[\frac{2\pi}{\lambda} * n_t \sin \theta_t * dx + \Phi \right] = 0 \quad (2)$$

Where θ_t denotes the refraction angle. Φ and $\Phi + d\Phi$ represent the phase discontinuities

at the points where the two paths intersect the interface. Additionally, dx denotes the distance between these points, while n_i and n_t represent the refractive indices of the two media, and λ represents the wavelength of the light. The resulting equation is known as the Generalized Snell's Law.

$$n_t \sin \theta_t - n_i \sin \theta_i = \frac{\lambda}{2\pi} \frac{d\Phi}{dx} \quad (3)$$

Equation (3) reveals that the refraction can have arbitrary directions by introducing a non-zero phase gradient $d\Phi/dx$. Similarly, for reflection, we have

$$n_r \sin \theta_r - n_i \sin \theta_i = \frac{\lambda}{2\pi n_i} \frac{d\Phi}{dx} \quad (4)$$

Where θ_r is the angle of reflection. There is a nonlinear relation between θ_r and θ_i . It is important to note that the angle of reflection (θ_r) is related to the angle of incidence (θ_i) through a nonlinear relationship, significantly different from the conventional specular reflection.

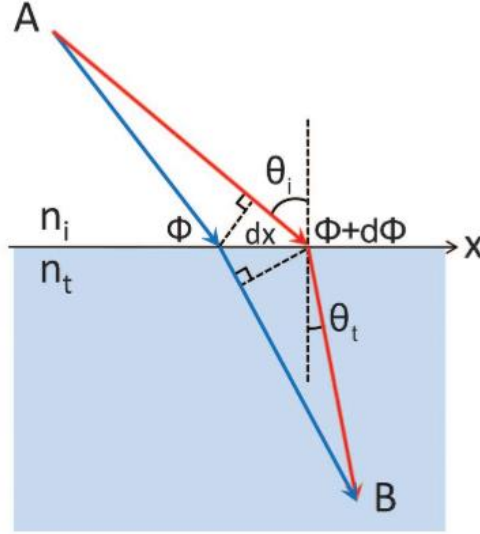


Figure 1.2. Schematic deriving the Generalized Snell's Law⁷. The interface between the two media is fabricated to introduce abrupt phase shifts.

1.2.2 Materials of Metasurface

Depending on the intended use, metasurfaces are designed to target various wavelength

bands, with the materials used varying accordingly. A material's optical properties are reflected by its refractive index (n) and extinction coefficient (k). For optimal performance, select materials with a high n value and a low k value at the target wavelength. This combination provides greater modulation depth and lower absorption loss¹¹. Metallic materials have first been used to create metasurfaces, such as the dual-polarity metalens fabricated by Chen et al. using Au and operating in the visible region (Figure 1.3a)¹². The metalens demonstrates convex and concave lens characteristics when exposed to right circularly polarized (RCP) and left circularly polarized (LCP) light, separately, because of the differing signs of the geometric phase. Although a plasmonic metalens has been fabricated for use in the visible region, its efficiency is limited due to the high ohmic loss of the metallic materials^{13,14}. To address this challenge, researchers have proposed a Metal-insulator-metal (MIM) structure that adds an Au layer to the existing plasmonic metasurface (Figure 1.3b)¹⁵. This additional Au film acts as a mirror to reflect the incident light. Consequently, this new structure has attained an 80% diffraction efficiency. However, the additional metal layer makes it impossible to implement a transmissive metasurface, increasing the need for nonmetallic materials.

Dielectric metasurfaces can achieve excellent transmittance and efficiency within the visible spectrum. Traditionally, silicon-based materials, such as crystalline silicon, amorphous silicon, and polycrystalline silicon, have been employed for producing dielectric metasurfaces, but these materials experience absorption losses at shorter wavelengths. Researchers have turned to alternative materials like Si_3N_4 , TiO_2 , and GaN to address this issue. However, the low refractive index of Si_3N_4 increases the height and aspect ratio, making the fabrication more challenging. The successful fabrication of TiO_2 and GaN structures requires a complex process that involves low-temperature atomic layer deposition (ALD)^{16,17} and high-aspect-ratio two-step dry

etching^{18,19}. In conclusion, material selection for metasurfaces highly depends on the working wavelength and application to ensure optimal performance and efficiency.

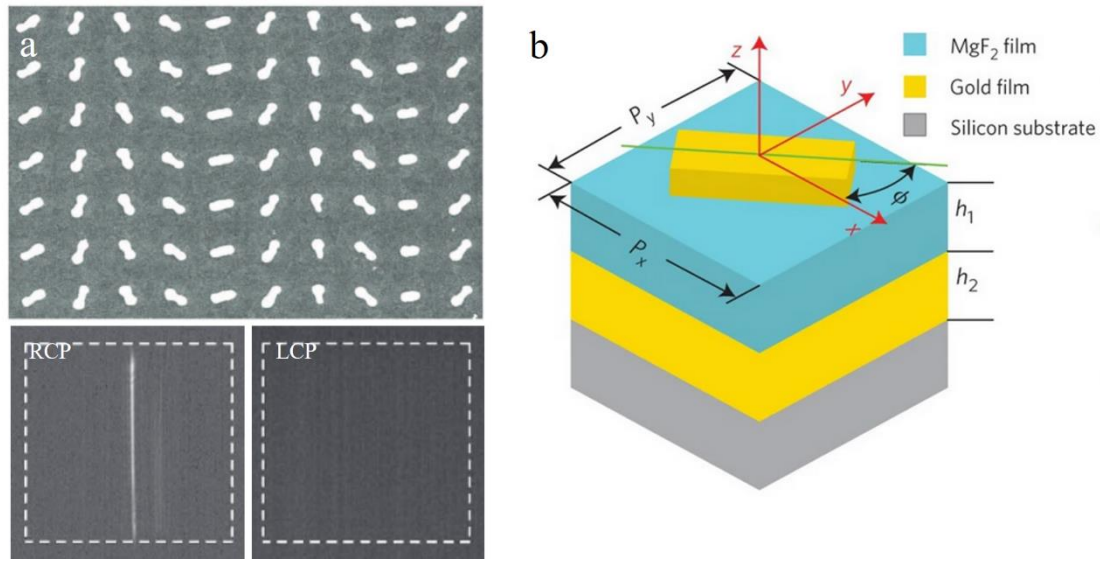


Figure 1.3. (a) SEM image (top view) of the dual-polarity metalens and optical microscope images of the real focal plane¹². (b) Structure of the MIM metasurface¹⁵.

1.2.3 Phase modulation

Regulating electromagnetic waves with conventional optical components such as lenses and prisms relies on the accumulation of phase delays as light propagates. This approach significantly hinders the miniaturization and integration of optical devices. In contrast, metasurfaces can achieve sharp phase shifts for incoming waves at sub-wavelength scales through light-matter interactions, enabling far more efficient wavefront modulation. This phase modulation is achieved by altering the shape, size, and in-plane rotation angle of the meta-atoms. Common techniques for phase modulation include resonant²⁰⁻²², propagation^{19,23}, and geometric phase^{24,25} methods.

1.2.3.1 Resonant phase modulation method

When metallic nano-atoms interact with light waves, the free electrons within them collectively oscillate and generate a phenomenon called localized surface plasmon

resonance (LSPR). By manipulating the geometry of the nanoscale structures, the resonance frequency can be shifted, which in turn enables the achievement of abrupt phase changes through resonance phase modulation. In 2011, Yu et al. demonstrated a gold atom array with a V shape can provide a 2π phase shift by combining a geometric phase and a resonant phase due to LSPR⁷. The polarization of the incident light on the gold atom induces both symmetric and antisymmetric modes (as shown in Figure 1.4a), and each mode has a distinct amplitude and phase due to different resonance conditions. By adjusting the atom length and angle between the rods, four meta-atoms with $\pi/4$ phase intervals can be obtained due to the resonance condition. Additionally, by rotating each of the four meta-atoms by 90° , another four meta-atoms with a π phase shift can be obtained. When combined, these eight meta-atoms can cover the 2π phase, as illustrated in Figure 1.4b.

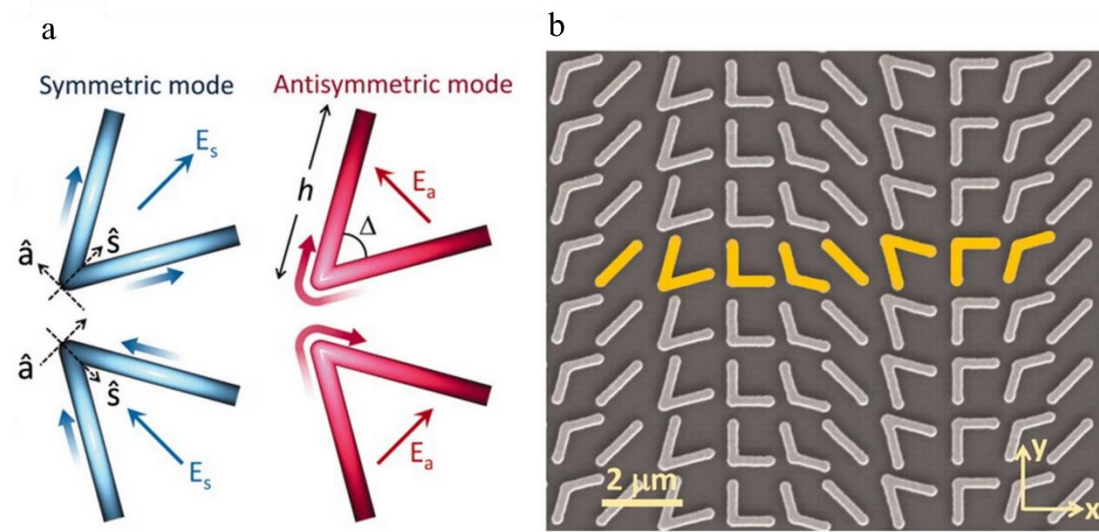


Figure 1.4. Phase modulation: resonant phase⁷. (a) Symmetric and antisymmetric mode of V-shaped gold atom. (b) SEM image (top view) of the plasmonic resonant-phase-based metasurface.

1.2.3.2 Propagation phase modulation method

In the method of propagation phase, each atom acts as a mini waveguide. Highly symmetric structures like cylinders are commonly used to impart polarization-

independent characteristics²³. Changes in phase occur as waves propagate through waveguides, which are described as

$$\Delta\Phi = \frac{2\pi}{\lambda} n_{eff} h \quad (5)$$

Where n_{eff} is the effective refractive index and h is the atom height. The dimensions of the atom determine the effective refractive index, and a series of atoms with varying dimensions, as demonstrated in Figure 1.5, must be created to achieve a 2π propagation phase. Additionally, selecting an appropriate period is crucial. If the period is too large, an additional propagation mode appears, reducing efficiency due to diffraction. Conversely, if the period is too small, it can lead to unwanted coupling between meta-atoms due to the decreased distance between them.

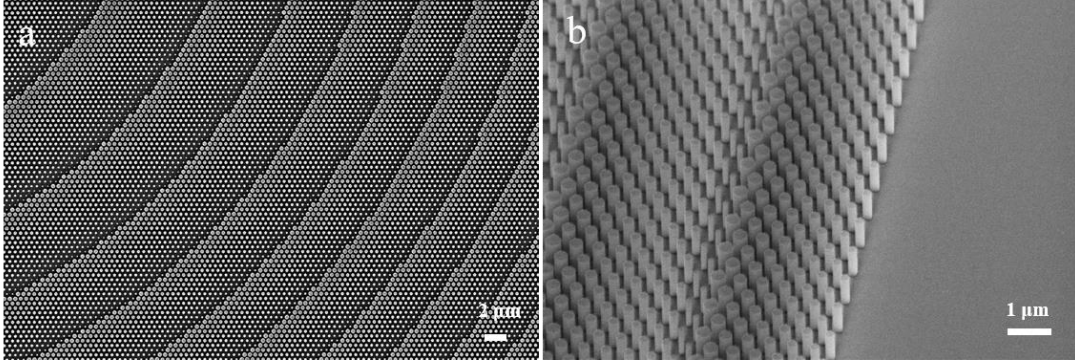


Figure 1.5. Phase modulation: propagation phase. (a) SEM images of a propagation-phase-based metasurface (Top view). (b) Side view of the same surface.

1.2.3.3 Geometric phase modulation method

For circularly polarized light $\mathbf{E}_{in} = [1 \pm i]^T$, the output electric field through an anisotropic meta-atom is

$$\mathbf{E}_{out} = \frac{t_1 + t_s}{2} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} + \frac{t_1 - t_s}{2} e^{\mp i 2\theta} \begin{bmatrix} 1 \\ \mp i \end{bmatrix} \quad (6)$$

The variables t_l , t_s , and θ represent the transmission coefficients along the long and short axes and in-plane rotation angles in this equation. The optical fields produce two perpendicular circular polarizations. The first term of Equation (6) indicates that the

output's circular polarization matches the incoming light and experiences no phase delay. In contrast, the second term shows that the output's circular polarization is directed oppositely and undergoes a geometric phase shift of $\mp i2\theta$, where $+$ and $-$ represent right and left circularly polarized, respectively^{26,27}. As a result, rotating identical anisotropic atoms can achieve broadband phase modulation with 2π phase coverage (Figure 1.6).

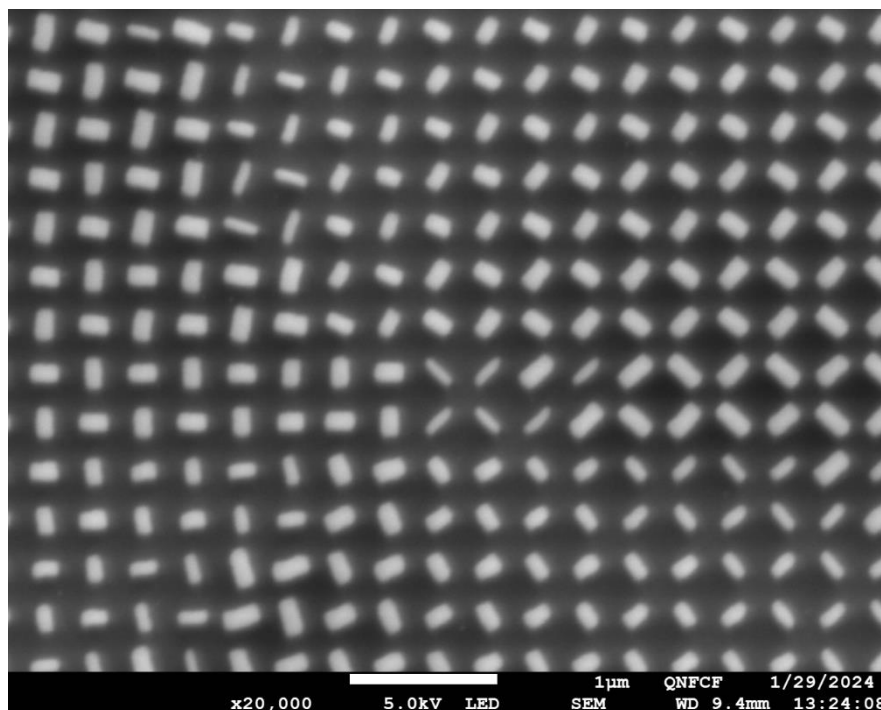


Figure 1.6. Phase modulation: geometric phase. SEM images of a geometric-phase-based metasurface (Top view).

1.3 Metalens and its recent progress

Metasurfaces can induce abrupt phase mutations in incident electromagnetic waves within sub-wavelength scales. By engineering a controlled phase profile, these metasurfaces can manipulate light beams, enabling functionalities such as twisting and focusing. Devices designed upon these principles are referred to as metalenses.

1.3.1 High NA metalenses

Implementing a high numerical aperture (NA) lens can significantly enhance the resolution of an optical system. Recently, metalenses with high NAs have been effectively employed in various applications, including transmissive eyepieces^{28,29}, direct laser lithography³⁰, and optical trapping^{31,32}. These advancements in optical technology hold great promise for developing highly efficient and effective optical systems in various academic and industrial fields. For a lens system, the NA is defined as

$$NA = n \sin \theta \quad (7)$$

Where n is the refractive index of the media and θ is the maximum deflection angle of the lens edge. The refractive index can be adjusted to achieve a higher n in Equation 7 by immersing the imaging system in a fluid such as oil^{33,34}. This technique applies to both conventional lenses and metalenses. The real advantages of metalenses over conventional lenses are the easy engineering of the focusing phase and the ability to control the diffractive energy distribution³⁵.

Traditional lenses rely on phase accumulation from different radial positions through various optical paths, which is modulated by the macroscopic thickness of the lens. To achieve a high NA, a lens with a specific diameter requires a rapid phase change at the edge. However, this poses a significant challenge as it requires an extremely large slope of thickness variation. On the other hand, meta-lenses can overcome this limitation by employing a compact arrangement of building blocks to generate arbitrary phases, thus allowing for rapid phase changes^{36,37}. Liang et al. utilized a hybrid optimization algorithm to create an ultrahigh-NA metalens that boasts an impressive NA of 0.98 and a focusing efficiency of 67% (see Figure 1.7a)³⁸. This algorithm employs four distinct optimization techniques - differential evolution, genetic algorithm, particle swarm optimization (PSO), and adaptive simulated annealing - to optimize the meta-atoms'

various parameters, including length, width, height, and period. Experimental results have confirmed that the metalens' focal spot has an FWHM of 274 nm, which aligns closely with both the simulation result (277 nm) and the Airy disk (279 nm) (see Figure 1.7b).

In metalenses, the diffraction of light deflected by the building blocks can be controlled by redistributing the diffracted energy, resulting in the concentration of energy at specific positions. This advanced modulating mechanism cannot be implemented using conventional lenses. An illustration of how diffraction energy redistribution can be used to create metalens with a high NA (0.99) was presented by Paniagua-Dominguez et al.³⁹. The team employed asymmetric scattering from nano-atoms, which allowed them to control the number and angle of diffraction orders. Figure 1.7c visually represents how they accomplished this by adjusting the unit cell's periods. Utilizing an array of asymmetric dimers, a concentration of energy to T+1 diffraction order can be achieved, resulting in the bending of light at an angle of 82° for planar, normally incident waves from the substrate side at a wavelength of 715 nm.

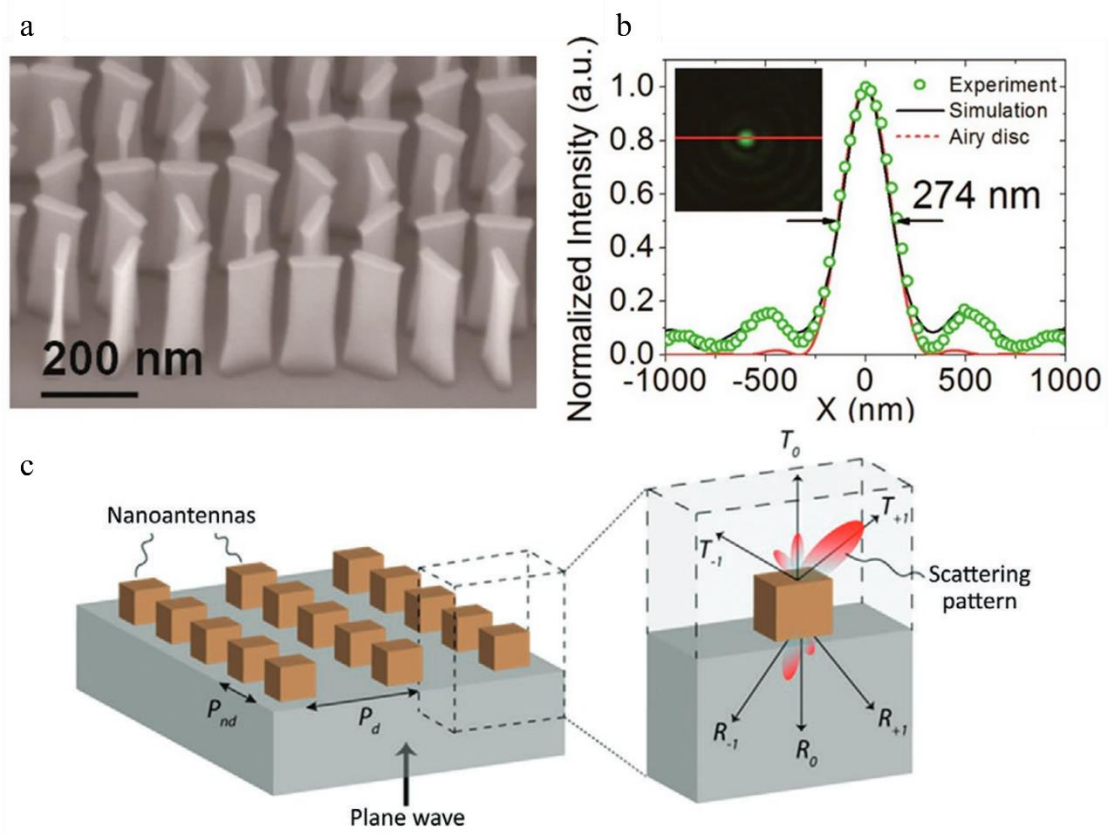


Figure 1.7. Example of high NA metalenses. (a) SEM image of the metalens with an NA of 0.98³⁸. (b) Measured, simulated, and ideal intensity profiles of focal spot³⁸. (c) Nano-atom arrays with controlled energy distribution among supported diffraction orders³⁹.

1.3.2 Achromatic metalenses

To achieve full-color imaging, it is imperative to correct chromatic aberrations. Chromatic aberration is a phenomenon that arises due to the variation in the refractive index of the medium to the wavelength. This leads to the polychromatic rays focusing on different spatial positions, thereby causing significant degradation in the image quality. Recently, there has been an active exploration of achromatic metalenses across a wide range of spectral regions, including the infrared⁴⁰⁻⁴⁴, visible light⁴⁵⁻⁴⁷, and ultraviolet^{48,49} regions.

Different from single wavelength metalenses, the phase profile of an achromatic

metalens is expressed as⁵⁰

$$\Phi(r, \lambda) = -\left[2\pi/\lambda * (\sqrt{r^2 + f^2} - f)\right] + \Phi_{shift}(\lambda) \quad (8)$$

Where r , λ , and f are radial coordinates on the metalens, the wavelength, and the focal length, respectively. The $\Phi_{shift}(\lambda)$ is introduced to represent for the phase dispersion of different wavelengths. We can transform this formula to obtain a new form:

$$\Phi(r, \lambda) = \Phi_f(r, \lambda_{max}) + \Phi_{dispersion}(r, \lambda) \quad (9)$$

$$\Phi_f(r, \lambda_{max}) = -\left[2\pi/\lambda_{max} * (\sqrt{r^2 + f^2} - f)\right] \quad (10)$$

$$\Phi_{dispersion}(r, \lambda) = -\left[2\pi(\sqrt{r^2 + f^2} - f) \left(1/\lambda - 1/\lambda_{max}\right)\right] + \Phi_{shift}(\lambda) \quad (11)$$

The basic idea of attaining an achromatic lens is to attain two distinct terms in Equation (9) by applying different phase modulation techniques. The constant Φ_f remains fixed at a specific position and is unaffected by the working wavelength. Its value can be attained by utilizing the previously introduced geometric phase. On the other hand, the second term, $\Phi_{dispersion}$, depends on the working wavelength and can be achieved through the appropriate design of each unit element of the metalens. Since this term is achieved by a completely different phase modulation method from the geometric phase, it can be easily combined without interference.

The broadband metalens developed by Wang et al. has an impressive focus efficiency of around 40% at an NA of 0.106, with a focal length of 235 μm and a wavelength range of 400-660 nm¹⁸. This lens incorporates a geometric phase and an integrated-resonant unit element (IRUE), which is composed of solid or inverse GaN-based structures arranged in a subwavelength periodic hexagonal lattice (as illustrated in Figure 1.8a). By carefully positioning and rotating these IRUEs on the substrate, the phase profile of the achromatic metalens was optimized. Similarly, Tsai et al. created metallic IRUEs and merged them with the geometric phase, resulting in broadband achromaticity in both visible (420-650 nm) and NIR (1200-1680 nm) regions (Figure 1.8b)⁴. Meanwhile,

Ali et al. produced an achromatic MgO-based metalens with an NA of 0.8, a focal spot of 182 nm, and a 200-400 nm wavelength, boasting a focus efficiency of 94%⁴⁸. Their metalens displayed impressive features such as high transmission, an ultrawide bandgap, and a high refractive index in the ultraviolet region.

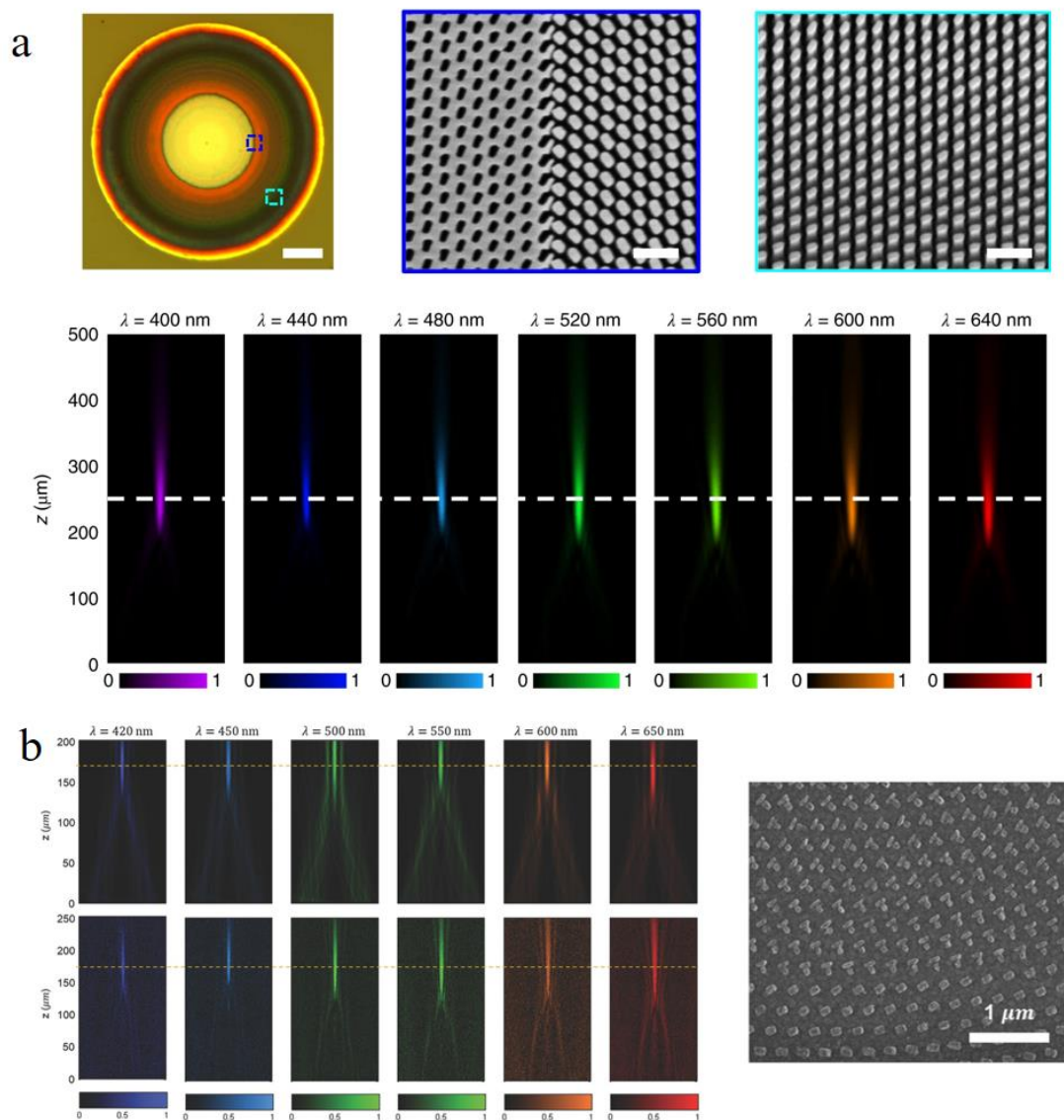


Figure 1.8. Example of achromatic metalenses. (a) Top: SEM images of the full lens (scale bar: 10 μm) and zoom-in views of it (scale bar: 500 nm). Bottom: Experimental focusing profile at each wavelength. White dashed lines indicate the focal plane¹⁸. (b) Left: Experimental focusing profile at each wavelength. Right: SEM image of meta-atoms⁴.

Another method to correct multiwavelength chromatic aberrations is spatial multiplexing. This practical approach combines various metasurfaces with different operational wavelengths in one surface area to provide the same focal length for multiple incident wavelengths. An example is the high-contrast dielectric metasurfaces fabricated by Faraon et al.⁵¹. These metasurfaces comprise amorphous silicon nanorods that mutually interleave different groups of meta-atoms within the same area. Each group provides the same focal position with its specific operational wavelength. Their experimental results in Figure 1.9a demonstrate that the meta-atom interleaving metalens generates a better-defined circular shape at the focal point. The operational wavelengths used in their experiment were 915 and 1550 nm, with an N.A. of 0.46.

Like conventional lenses, metalenses can be vertically stacked to form a multi-layer achromatic meta-lens assembly. Each meta-lens operates independently of the incident wavelength with minimal spectral crosstalk between the lenses, achieving the same focal position. Zhou et al. created a multilayer dielectric metalens capable of operating at various wavelengths in the infrared region (1100 nm, 1400 nm, and 1680 nm). The metalens achieved a focal efficiency of 48% (design) and 38% (measurement) at 1180 nm and 56% (design) and 52% (measurement) at 1680 nm⁵². The team constructed a two-layer metalens with Si nanorods. It determined the desired phase by combining the radii of the cylindrical meta-atoms of each layer. Another team, Avayu et al., demonstrated an assembly of plasmonic achromatic meta-lenses composed of disc-shaped nanoparticles of varying sizes and materials, effectively converging red, green, and blue light to the same focal point (Figure 1.9b)⁵³.

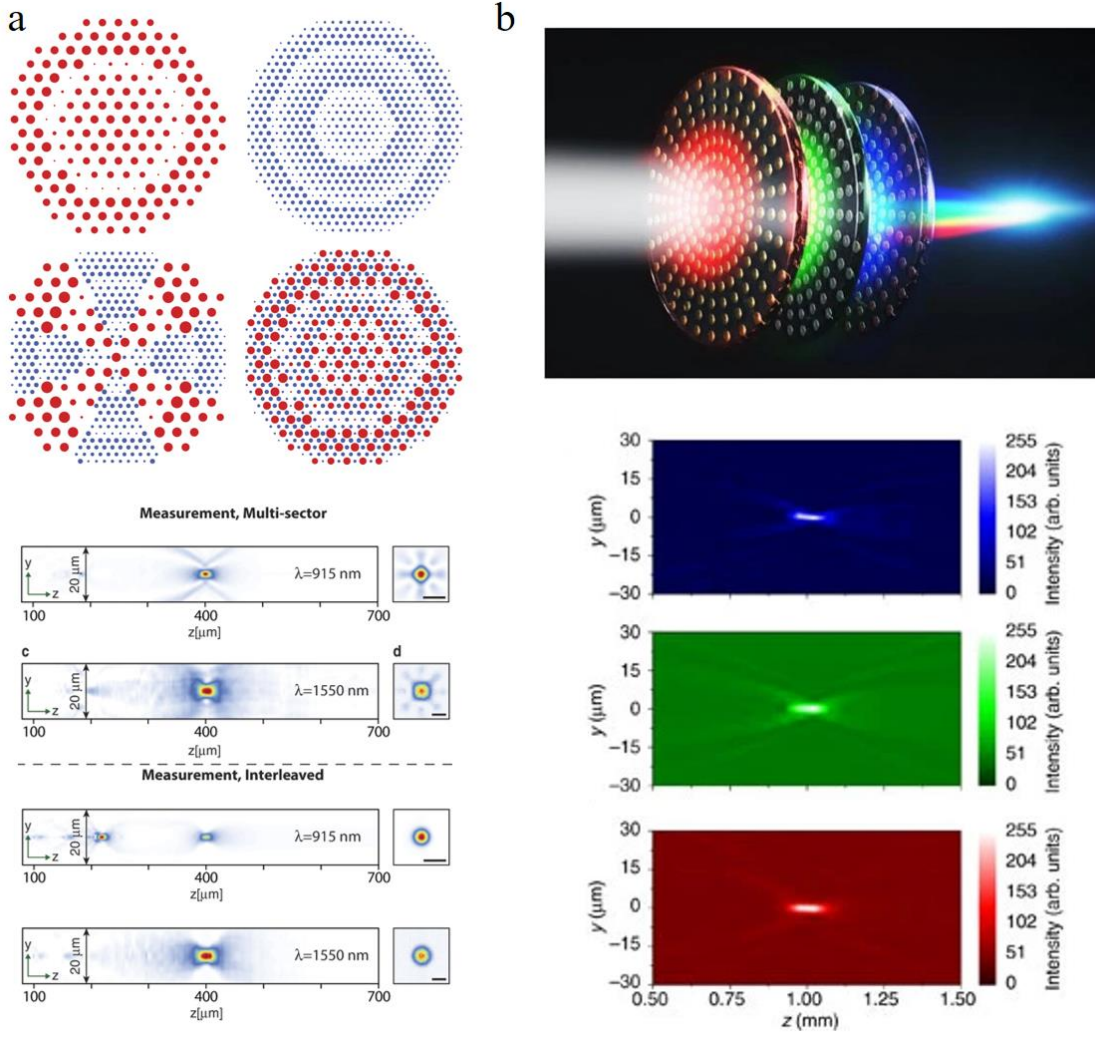


Figure 1.9. Examples of achromatic metalenses achieved by multiplexing and stacking. (a) Top: schematic of multi-sector and interleaving multiplexing. Red and blue pixels represent the design with λ_1 and λ_2 , respectively. Bottom: measurement results at the focal plane⁵¹. (b) Top: schematic of stacked metalenses. Bottom: intensity profiles of red, green, and blue lights⁵³.

1.3.3 Focal length tunable metalenses

Adjusting the focal length in zooming devices, such as cameras, microscopes, telescopes, and endoscopes^{54,55}, is crucial. However, conventional optical systems achieve zooming by combining multiple lenses and adjusting their axial distances, which increases the system's size and necessitates complex integration techniques. Fortunately, metalenses offer a solution to this problem. A single dynamically tunable

metalens can modify the focal length, allowing for a smaller and simpler integration.

1.3.3.1 Inherent Tunability

A metalens can be tuned by adjusting either the position or morphology of its building blocks. Each unit provides a consistent phase in the former, but rearranging the modulators generates a variable phase distribution. In the latter, the generated phase of each modulator can be tuned while its position remains constant. In either case, the result is an integral response that enhances the metalens function.

PDMS is a commonly used material with high stretchability often employed in creating reconfigurable metalenses⁵⁶. These lenses can be adjusted by external mechanical forces⁵⁷. Ee et al. developed a metasurface that acts as an ultrathin flat zoom lens at a wavelength of 632.8 nm (Figure 1.10a)⁵. By stretching the substrate, the positions of plasmonic Au nanorods can be adjusted, allowing for tuning of the wavefront shape. Their metalens fabricated on PDMS is shown to have variable focal lengths ranging from 150 μm to 250 μm . It is also possible to change the morphology of the building blocks to achieve similar effects. Zhu et al. demonstrated this concept with a planar random access reconfigurable metamaterial (RARM), where the resonant properties for individual split rings can be continuously controlled by changing the metal filling fraction⁵³. The RARM-based meta-lenses achieve a tunable focal distance by adjusting the spatial phase gradient.

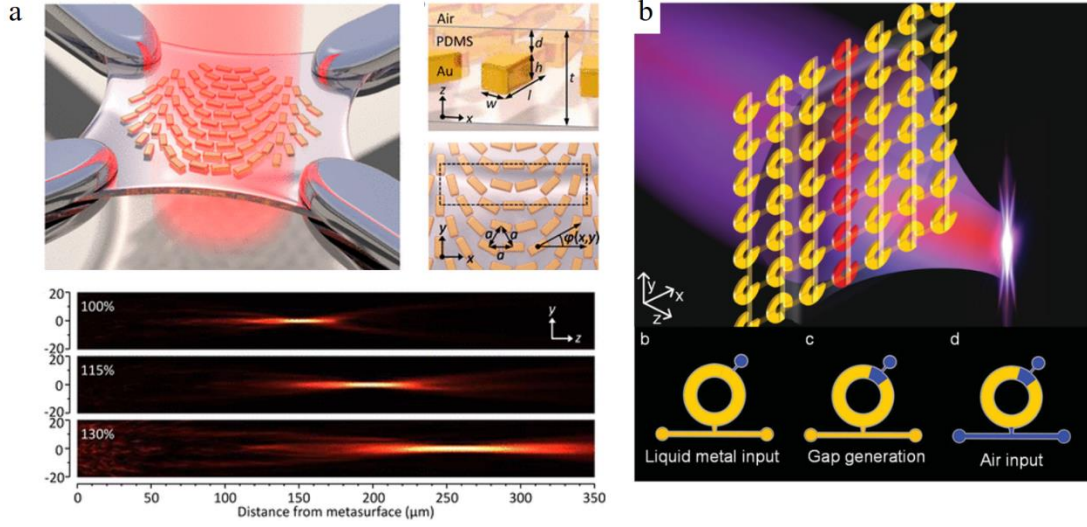


Figure 1.10. Examples of stretchable and tunable metalenses. (a) Top: schematic of the stretchable metalens on PDMS. Bottom: intensity profiles measured with no stretching, stretching at 15%, and stretching at 30%⁵. (b) Schematic of the tunable metalens. The resonant properties of each ring unit can be controlled by adjusting the fraction of mercury and gas⁵⁸.

1.3.3.2 External Tunability

Rather than altering the metalens functions directly, external tunability regulates how a metalens assembles. Regarding traditional lens systems, the Alvarez principle is a widely used method for creating variable focal lengths⁵⁹⁻⁶⁶. This system utilizes two opposing parallel lenses, which increase the depth of focus, and a cubic function defines the phase profile, resulting in focal length changes caused by lateral displacement. This technique can also be applied to meta-lenses. In a proof-of-concept study by Zhan et al., they developed an Alvarez meta-lens composed of silicon nitride nanorods⁵⁹. With different lateral displacements, the summed phase of the two lenses is changed, as demonstrated in Figure 1.11a. This large-area device has a varifocal length of 2.5 mm. The system's aperture was later expanded up to 1 cm to achieve a larger varifocal length of 6.62 cm. A modified version of the Alvarez system has been developed, in which the two lenses are rotated coaxially instead of moving in parallel, inspired by the Moiré

lens⁶⁷⁻⁶⁹. The research by Cui et al. showcases a rotationally adjustable polarization-dependent varifocal metasurface⁷⁰, while Yilmaz et al. demonstrated a polarization-independent varifocal metasurface⁷¹. The translational and rotational versions of the Alvarez systems are highly adjustable and provide excellent control over optical responses. However, when working on a microscopic scale, precision alignment and manipulation are required, as misalignment can negatively impact the focusing efficiency.

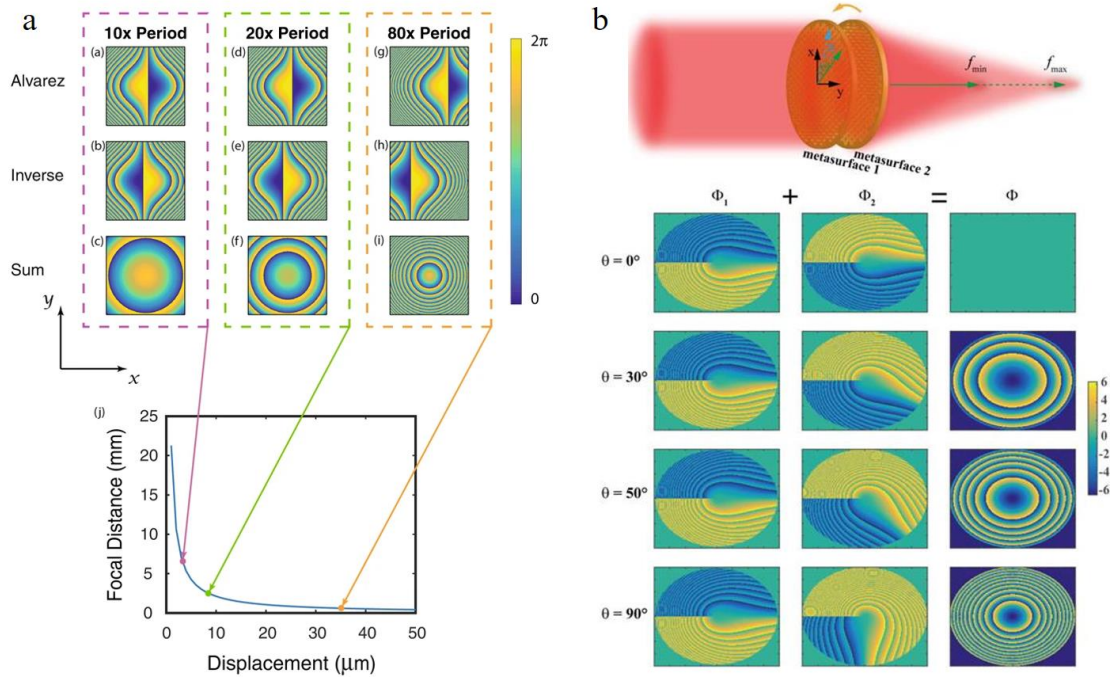


Figure 1.11. Examples of the focal distance adjusted by laterally displacing and rotating two surfaces. (a) Schematic of the phase in response to x displacement⁵⁹. (b) Schematic of a varifocal metalens composed of two combined metasurfaces with mutual rotation⁶⁹.

1.3.4 Integrated metalenses

Metalenses have the advantage of being directly fabricated onto the surface of other optical devices compared to conventional lenses. This allows for the integration of metalenses with fibers, making it possible to achieve flexible optical trapping, fiber-optic communication, or endoscopic imaging when a metalens is created on the tip of a

fiber. Plidschun et al. recently demonstrated optical trapping by producing ultrahigh-NA metalens on the tip of a functionalized fiber (Figure 1.12a)³¹. A metalens was fabricated using a direct laser writing system by increasing the adhesion through the silanization process on the fiber tip. The 660-nm-wavelength light passing through the single-mode fiber is expanded through the spliced multimode fiber to the size of the metalens aperture and then focused through the metalens at the end of the fiber. Ren et al. also fabricated achromatic metalens on a single-mode fiber end face to address the chromatic aberration caused by conventional end-face lenses⁷². They printed a hollow tower on the end of the single-mode fiber for beam expansion and fabricated the metalens using two-photon polymerization. A thin spacer layer was placed between the hollow tower and the metalens to minimize transmittance loss. The implemented metafiber displayed achromatic and polarization-insensitive focusing over the 1.25–1.65 μm telecommunication band, as shown in Figure 1.12b.

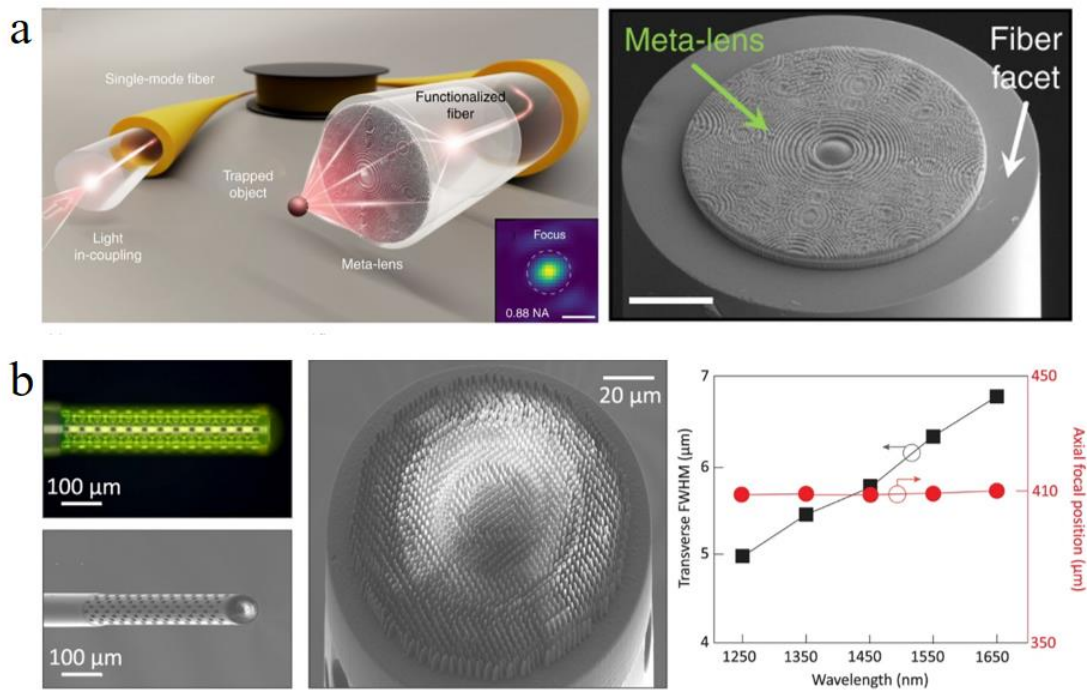


Figure 1.12. Integrated metalenses with optical fibers. (a) Schematic and SEM image of a metalens on fiber³¹. (b) Images of metal fiber and its FWHM/focal length at different wavelengths⁷².

1.3.5 Large field of view (FOV) metalenses

Wide-angle imaging is crucial for various applications, including augmented reality, microscopy, landscape photography, and image projection. However, the field of view (FOV) is often limited by off-axis aberrations, particularly coma aberration. Achieving large FOV imaging with conventional optics presents challenges. Traditionally, a complex lens system involving multiple lenses is employed to address both axial and off-axis aberrations. For enhanced miniaturization, flat metalenses that can ideally focus light at any incident angle (θ_i) are desired, with the corresponding ideal phase profile being dependent on the incident angle:

$$\varphi(r, \lambda, \theta_i) = -\frac{2\pi n}{\lambda} \left(r \sin \theta_i + \sqrt{(r - f \tan \theta_i)^2 + f^2} - \frac{f}{\cos \theta_i} \right) \quad (12)$$

Three types of metalenses can be utilized to achieve a large field of view (FOV): Singlet, Chevalier Landscape, and Doublet, as illustrated in Figure 1.13a⁷³. The Singlet metalens experiences limitations in FOV due to increased wavefront aberration root mean square (WAFrms) with varying incident angles, necessitating further manipulation for effective wide-angle imaging. For example, to obtain wide-field microscopy imaging with a FOV of 18°, an array of metalenses was developed to cover a broad area of CMOS image sensors, enabling the completion of a fully stitched wide-field image⁷⁴.

The second type, the Chevalier Landscape metalens, distributes light based on different incident angles, directing them to various areas of the metasurface. This design makes surface phase management more straightforward. Engelberg et al. successfully utilized the Chevalier Landscape metalens to create a compact camera for wide-angle outdoor near-infrared imaging, achieving a FOV of approximately 30°⁷⁵. This was accomplished using a Huygens metalens patterned with a-Si nanopillars and a longer focal length of 3.36 mm, which is more adept for outdoor imaging, providing the

enhanced angular resolution needed for recognizing facial features at distances of several meters.

The third type is the Doublet metalens, which integrates multiple layers of metasurfaces. This design's primary advantage lies in its ability to combine various functionalities. For instance, as depicted in Figure 1.13c, Kim et al. designed and optimized the Doublet metalens to achieve a FOV of 30° while also achieving high numerical aperture (NA) focusing across three visible wavelengths: 445, 532, and 660 nm⁷⁶.

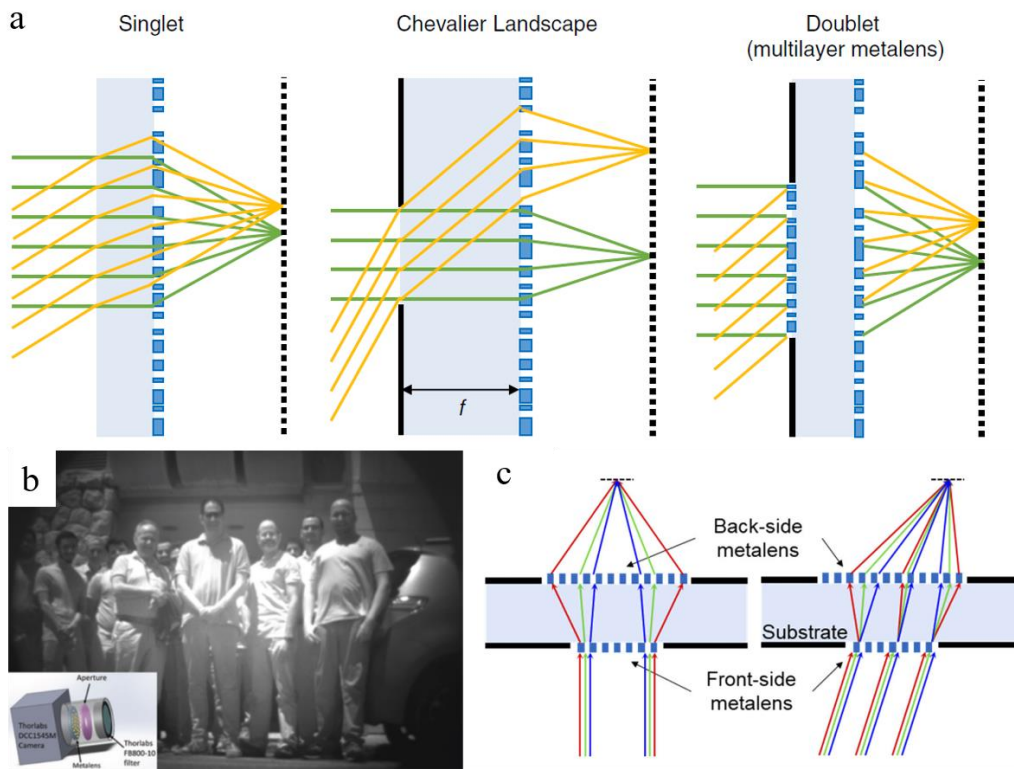


Figure 1.13. Large FOV metalenses. (a) Schematic of three types of Large FOV metalenses⁷³. (b) Metalens outdoor imaging⁷⁵. (c) Design of a metalens that combines achromatic properties with a large FOV⁷⁶.

1.4 Other applications of Metasurface

1.4.1 Holography

Metasurfaces can create holograms by manipulating the amplitude and phase of electromagnetic waves simultaneously. In 2013, Ni et al. introduced a complementary V-shaped groove array made from a 30 nm gold film on a glass substrate, successfully producing a holographic image of the word "PURDUE" when illuminated by a visible laser at 676 nm, as illustrated in Figure 1.14a⁷⁷. Another method for achieving holography involves using transmissive dielectric Huygens' metasurfaces. Chong et al. demonstrated a polarization-insensitive holographic Huygens' metasurface utilizing silicon resonant meta-atoms optimized for telecommunication wavelengths at 1477 nm (Figure 1.14b)⁷⁸. Furthermore, Zhang et al. achieved low-loss metasurface holography in the deep ultraviolet range (266 nm) by employing HfO₂ as the metasurface material, as shown in Figure 1.14c²⁴.

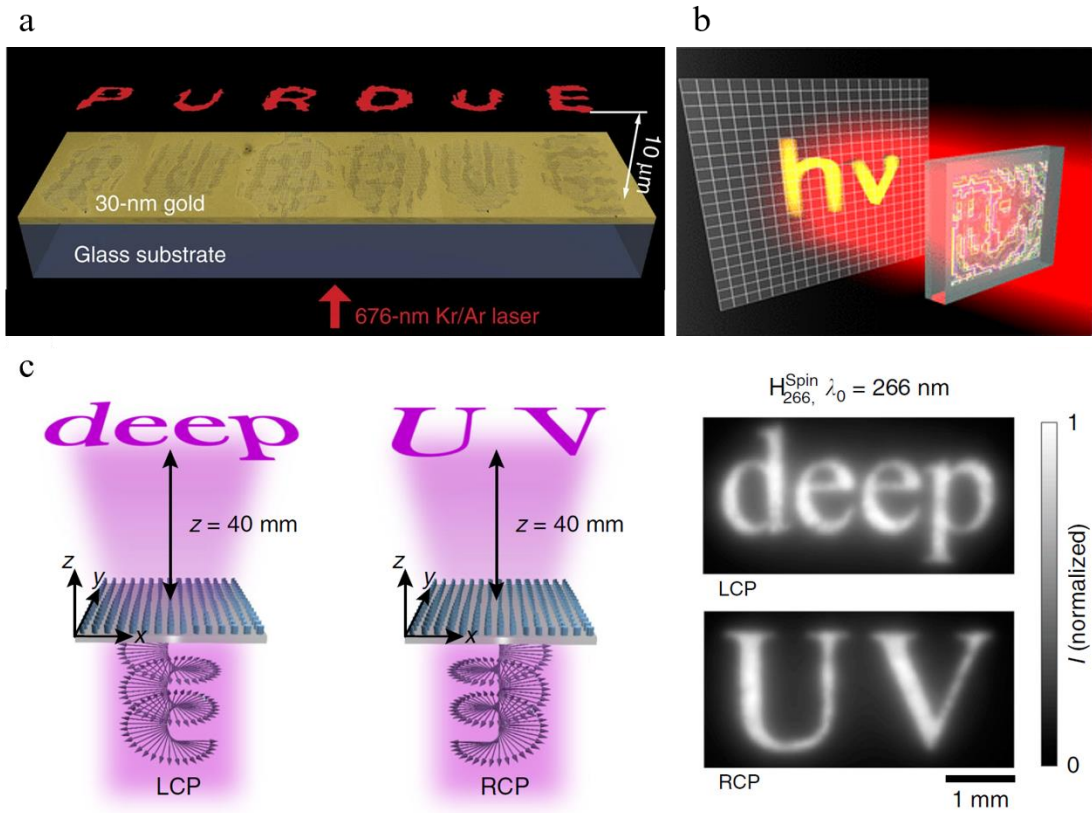


Figure 1.14. Typical metasurface holography works. (a) Metallic grooves produce a single-color

holographic image of the word “PURDUE.”⁷⁷ (b) Conceptual image where a $\lambda = 1477$ nm laser beam passes through a holographic metasurface to produce a two-dimensional hologram image behind the metasurface⁷⁸. (c) Measured holographic images projected by metasurface in the $z = 40$ mm plane under LCP and RCP illumination at 266 nm²⁴.

Previous metasurface holograms were mainly created for specific wavelengths and single angles of incoming light. However, recent metasurface holography progress has introduced methods allowing for wavelength-multiplexed and angle-multiplexed capabilities. By incorporating multiple resonators with unique resonance wavelengths within each meta-unit cell, these designs can simultaneously manipulate beams of multiple wavelengths. In 2015, Huang et al. showcased a phase-modulated multicolor meta-hologram with a two-dimensional pixel array, shown in Figure 1.15a⁷⁹. Each pixel contained four subpixels—two for blue, one for red, and one for green—arranged in a 4×4 pattern of aluminum nanorods. The configuration of nanorods in each subpixel was specifically designed for different colors, leading to distinct reflection spectra based on geometric variations. Expanding on this idea, full-color metasurface holograms can be achieved by modulating the intensity and phase of RGB (red, green, and blue) lasers, a process called color mixing. Further progress by Li et al. employed off-axis illumination, directing three laser beams (red, green, and blue) toward the metasurface from various tilted angles. This innovative approach allowed for the extraction of the three main color components and facilitated the creation of secondary superimposed colors, including cyan, magenta, yellow, and white, as depicted in Figure 1.15b⁸⁰.

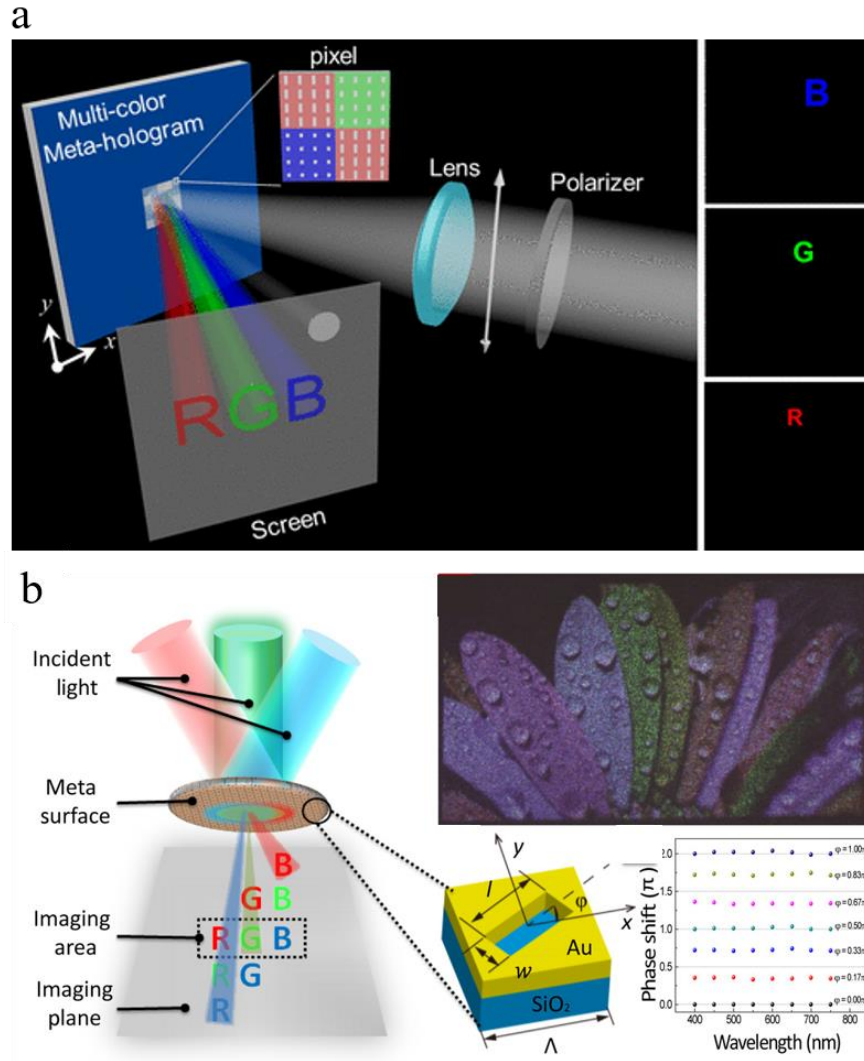


Figure 1.15. Wavelength-multiplexed metasurface holography. (a) Schematic of the multicolor meta-hologram designed for linearly polarized light. This phase-modulated multicolor meta-hologram enables the creation of polarization-dependent images in three primary colors⁷⁹. (b) Schematic of the off-axis illumination technique employed for the full-color meta-hologram. The top right image shows the experimental results of a vibrant flower image produced with plasmonic nanoslit antennas⁸⁰.

The angular response characteristics are essential in diffractive optics, particularly in gratings, diffractive optical elements, and metasurfaces. This optical property provides new design freedom for metasurface holography. In 2017, Kamali et al. introduced an angle-multiplexed metasurface design that utilized dielectric U-shaped units with high

reflective contrast⁸¹. This configuration facilitated independent phase control under a TE-polarized light beam at incident angles of 0° and 30° . Distinct images were encoded as different phase profiles of the metasurface for these varying angles. As a result, the angle-multiplexed metasurface hologram generated two separate projected images at 0° and 30° , as depicted in Figure 1.16.

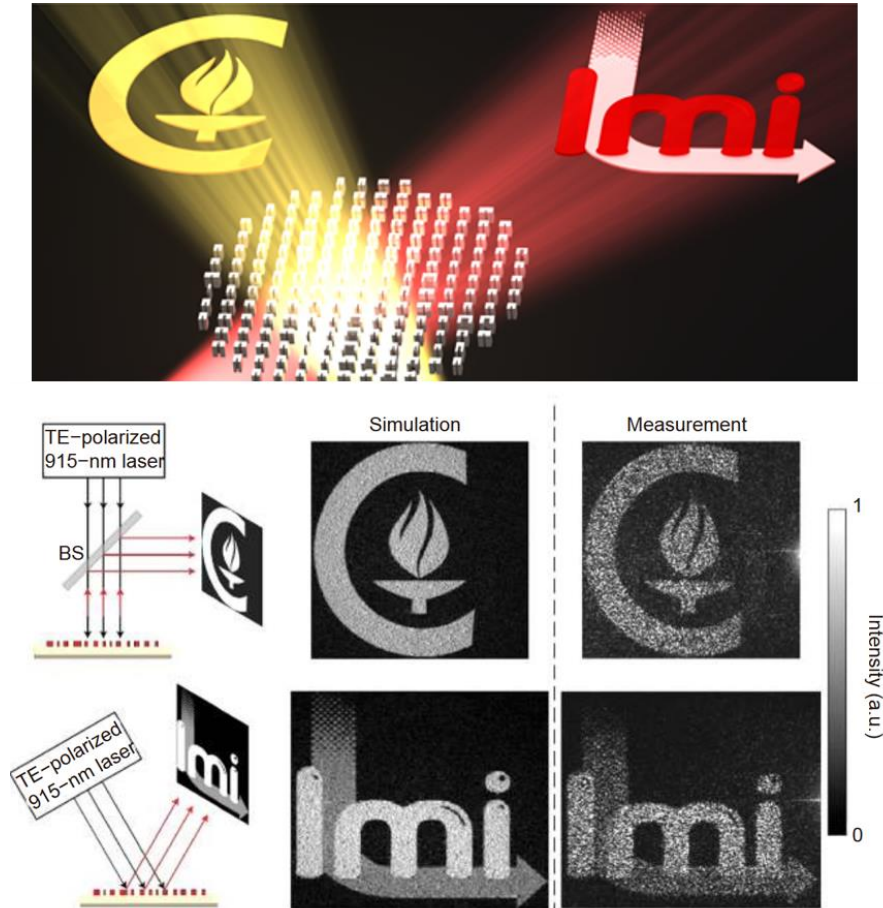


Figure 1.16. Angle-multiplexed metasurface holography. Two independent images were projected at 0° and 30° separately⁸¹.

1.4.2 Self-accelerating beam generation

Self-accelerating beams are notable for their unique properties, such as transverse acceleration, diffraction-free propagation, and the ability to self-heal when encountering obstacles in free space. In parallel, metasurfaces constructed from

dielectric or metallic subwavelength structures have garnered significant interest. Their precise control over electromagnetic waves enables the effective generation of these self-accelerating beams, opening up various intriguing applications. In 2020, Zhang et al. utilized a versatile platform of catenary-inspired dielectric metasurfaces to create continuous wavefronts with high diffraction efficiency, approaching 100%, across a broad spectral range of 9 to 13 μm ⁸². Another research group used HfO₂ as the metasurface material, achieving a self-accelerating beam in the near-UV region ($\lambda = 364$ and 325 nm)²⁴. The measured efficiencies at the $z = 5$ mm plane are $(46.75 \pm 2.31) \%$ (B_{364}) and $(67.42 \pm 4.43) \%$ (B_{325}). The measured deflection in the z -planes closely matches the simulated results, as shown in Figure 1.17.

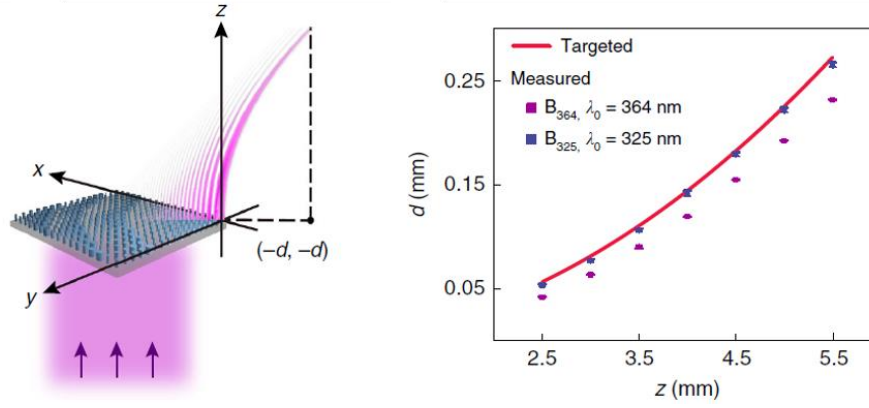


Figure 1.17. Schematic of generation of a self-accelerating beam by a metasurface and measured transverse deflection in different z planes²⁴.

1.5 Market and our research

The global metalens market reached approximately \$41.6 million in 2024, with a projected compound annual growth rate (CAGR) of 80% through 2031, ultimately reaching \$2.4 billion by that year. Near-infrared (IR) and infrared metalenses lead the market, accounting for a 70% share. The first commercial metalens was developed by Metalenz Inc. in 2022, successfully replacing the camera stack in Time of Flight systems with a single near-infrared metalens. Despite this advancements, metalenses

have not achieved widespread commercialization due to several challenges, such as the trade-off between high performance and high NA, as well as concerns regarding fabrication consistency and the complexities of mass production. Therefore, our research focuses on investigating and enhancing the fabrication methods for near-IR and IR metalenses.

Chapter 2: Fabrication methods of metalenses

This chapter summarizes the commonly used fabrication methods for metalenses and introduces the techniques essential to my projects: thin-film deposition, e-beam lithography, and dry etching.

Creating a metasurface with thousands of nano-atoms requires a complex manufacturing process that demands precise control. Several methods are currently available for achieving metasurfaces, including lithography-etching, nanoimprint (NIL), lithography-deposition, laser direct writing, and 3D printing. My projects in Chapters 3-5 will be on the lithography-etching process, particularly e-beam lithography.

2.1 Photolithography-etching-based fabrication

In Photolithography-etching-based metalens fabrication, a standard process flow is depicted in Figure 2.1. Photolithography is a process that involves writing on a substrate coated with a photoresist using light photons. A chemical reaction occurs by illuminating specific polymers (photoresists) with light, which is used to pattern the substrate selectively⁸³. Ultraviolet (UV) and deep ultraviolet (DUV) light sources are commonly used. When photons strike the photoresist, they cause a chain-scission or cross-linking reaction between the polymer chains⁸⁴. Whether the photoresist experiences chain-scission or cross-linking depends on the resist's chemical composition, which classifies resists as positive or negative photoresist, respectively. The contrast, sensitivity to photon wavelength, resistance to further etching process, and line edge roughness for each class of photoresist depend on the specific chemical composition of the resist⁸⁵. Contrast refers to the difference in depth/height of the

photoresist in the photon-exposed areas versus unexposed areas⁸⁶. Sensitivity refers to the photon energy per unit area (dose) required to expose the resist fully. The selective illumination of the resist is done using a photomask with transparent and opaque areas that selectively block light.

Maskless photolithography is a technique for selectively illuminating a surface using a laser beam and a spatial light modulator (SLM). Unlike traditional photolithography, this method does not require a physical mask. Instead, the desired pattern is designed in computer-aided design (CAD) software and transferred to the photolithography system in a readable format (usually a gds file)⁸⁷. This is commonly used in research labs as it is less time-consuming and costly than fabricating a physical mask and allows for easy pattern redesign.

Following the photoresist patterning, an etching process transfers the pattern onto the metasurface material. She et al. effectively employed a combination of photolithography and reactive ion etching (RIE) to create a large area of metalens, as shown in Figure 2.2⁸⁸. It is worth noting that the atoms in their images were relatively large, measuring 1 μm . This is because standard photolithography equipment is not suitable for patterning nanostructures. While more advanced techniques like deep UV and extreme UV lithography with immersion systems can achieve finer patterns⁸⁹, these methods are not widely available in research labs or universities around the globe.

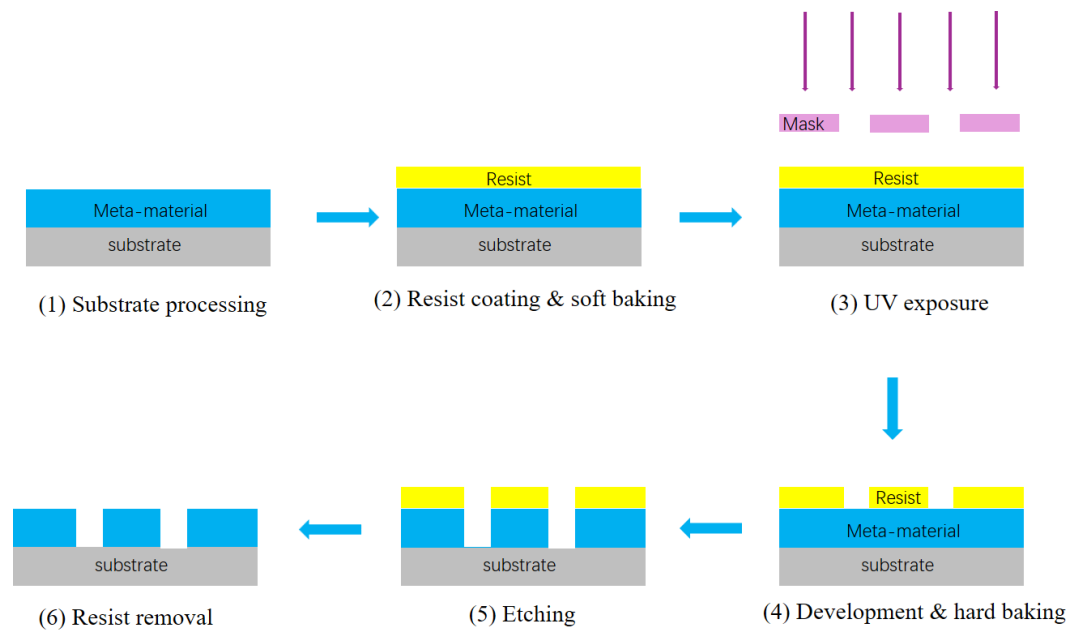


Figure 2.1. Process flow of a typical photolithography-etching-based fabrication.

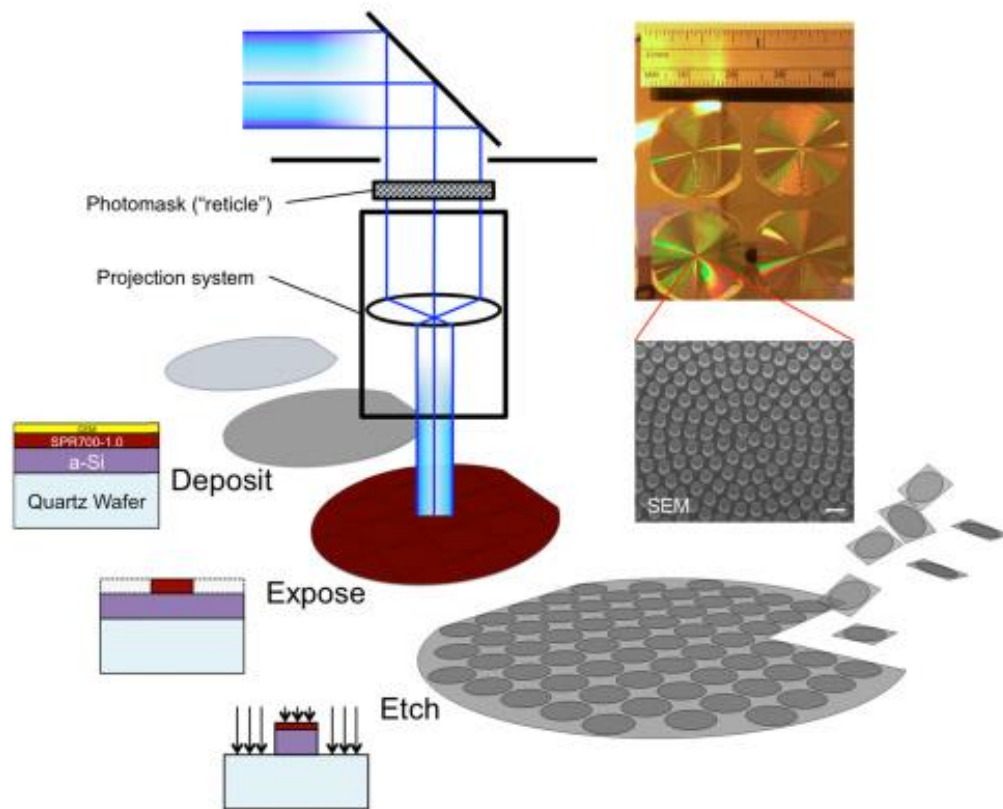


Figure 2.2. schematic and images of a large area of metalenses⁸⁸. Scale bar: 2 μm .

2.2 E-beam lithography-etching-based fabrication

The e-beam lithography-etching process is currently the most widely used technique for fabricating metalenses. Figure 2.3 illustrates a typical process flow for this method, encompassing thin film deposition, e-beam lithography, lift-off, and dry etching.

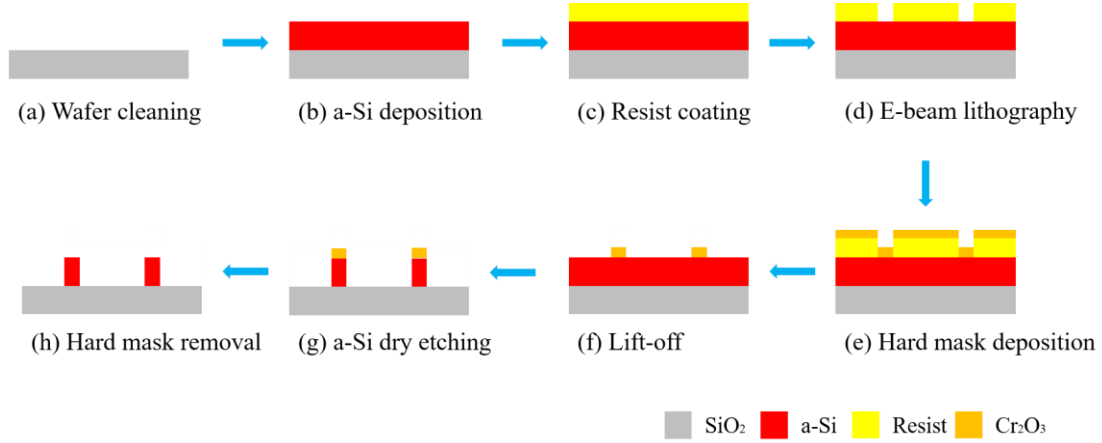


Figure 2.3. Process flow of a typical e-beam lithography-etching-based fabrication.

2.2.1 Thin film deposition

Film deposition is typically the first step of metalens fabrication. A variety of methods can be used to achieve specific applications. Thin-film deposition can be divided into chemical vapor deposition (CVD) and physical vapor deposition (PVD). CVD involves low-pressure chemical vapor deposition (LPCVD), plasma-enhanced chemical vapor deposition (PECVD), and atomic layer deposition (ALD), while PVD consists of thermal/e-beam evaporation and sputtering. Each technique has its own strengths, depending on the deposited materials, target thickness, and desired properties of the thin film. Typically, CVD is used for the deposition of dielectric materials such as SiO₂, SiN. In contrast, PVD is usually used for the deposition of metals or metal oxides such as chromium, aluminum, and their oxides. Importantly, one material deposited using different techniques may exhibit different properties and qualities.

For the fabrication of dielectric metalenses, various materials can be deposited using

chemical vapor deposition (CVD), including a-Si (via PECVD), SiN (via PECVD or LPCVD), and TiO₂ (via ALD). Figure 2.4 illustrates the steps involved in the thin-film growth process during CVD⁹⁰. In a typical CVD procedure, a substrate is placed in a heated reaction chamber, into which one or more volatile precursor gases are introduced. These gases flow through the chamber and reach the surface of the substrate, where they adsorb, react, and decompose to create a solid layer. Simultaneously, any volatile by-products generated during the reaction are expelled by the gas flow, ensuring a uniform film growth over time. In this thesis, a-Si was deposited using PECVD, allowing energetic reactions to occur at lower temperatures than LPCVD.

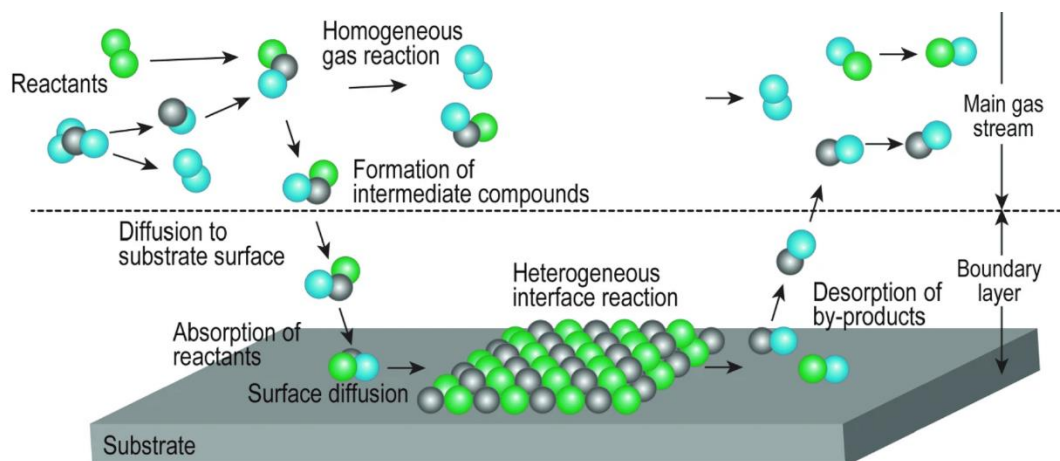


Figure 2.4. Overview of a typical chemical vapor deposition⁹⁰.

2.2.2 E-beam lithography

Electron beam lithography (EBL) is a process where electrons are used to 'write' on a substrate⁹¹. This method is like photolithography but does not require a mask, and the electron-beam resists differ from photoresists. The electron beam has a smaller wavelength than photons, which allows for sub-10 nm resolution⁹². The process involves using a series of magnetic lenses to focus the beam on the sample surface, unlike photolithography, which uses optical lenses. Instead of a physical mask, the electron beam is deflected to strike desired substrate areas. The entire process is conducted in a high vacuum to prevent electron scattering and achieve optimal beam

control.

Electron beam resists are polymer materials that respond to electron beams, similar to how photoresists react to photons. These resists can be either positive tone or negative tone, just like photoresists. The most used positive tone resist for EBL are PMMA (poly-methyl methacrylate)⁹³ and ZEP520⁹⁴, both of which contain long-chain polymers that break when exposed to the electron beam. Conversely, HSQ (hydrogen silsesquioxane)⁹⁵ is a popular negative EBL resist that transforms from its box-like molecular structure to become like oxide when exposed to the electron beam.

In Figure 2.5, a standard process flow for fabricating metalens using E-beam lithography-etching is displayed. As in photolithography, the metasurface material is initially deposited, followed by resist coating and patterning. However, in this case, a lift-off process is employed to create a hard mask pattern instead of using resist directly as a mask. This is because resist tends to be etched easily, which can cause nanostructures to take on undesired shapes. Hard masks maintain their dimensions and shapes more effectively during etching processes, even under harsh conditions. This dimensional stability is crucial for achieving precise feature sizes and shapes, especially in the fabrication of small structures where dimensional accuracy is critical.

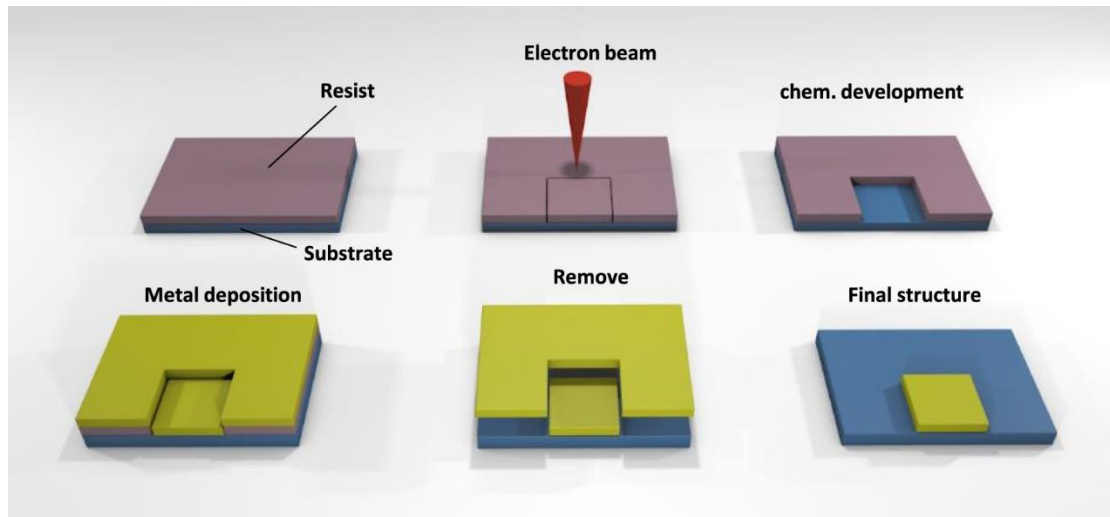


Figure 2.5. Process flow of a typical E-beam lithography⁹⁶.

2.2.3 Etching

Two primary methods for removing materials are wet etching and dry etching. Wet etching involves using chemical solutions to etch desired materials, while dry etching generates plasma in the etch chamber. However, wet etching is unsuitable for nanostructure etching due to its isotropic nature, as shown in Figure 2.6a, which depicts the lateral etch of wet etch.

In contrast to wet etching, dry etching offers the ability to achieve anisotropic results. The key component in dry etching is plasma, which is generated from fully or partially ionized gas. Plasma maintains electrical neutrality by balancing positive and negative charges. By energizing electrons, plasma can be created in a high-energy state, facilitating processes that would otherwise be impossible under normal conditions. Plasma etching functions through three primary mechanisms: the first involves the removal of material solely through chemical reactions; the second combines chemical reactions with physical bombardment; and the third focuses on material removal purely via physical bombardment. As a result, plasma etching can be classified into three distinct types: chemical plasma etching (PE), reactive ion etching (RIE), and physical

ion beam etching (IBE). As illustrated in Figure 2.7, PE produces isotropic profiles characterized by high etch rates and selectivity, while IBE yields positively tapered profiles with lower selectivity and etch rates⁹⁷. RIE serves as a hybrid method, effectively integrating the advantages of both PE and IBE. This synergistic combination of physical sputtering and the chemical activity of reactive species allows for precise control over etching profiles, achieving both high etch rates and selectivity.

RIE is the most widely used method in the semiconductor industry. This technique generates plasma composed of ions and radicals, facilitating both physical and chemical etching processes. RIE employs two mechanisms to achieve anisotropic etching, as illustrated in Figure 2.6b. Firstly, ions are propelled by a built-in bias, leading to ion bombardment—which constitutes physical etching. This bombardment disrupts the unreactive surface of the sample, creating a damaged layer on the unprotected horizontal areas while causing significantly less damage to the sidewalls. This disruption enhances the reactions between the sample and the radicals present. Secondly, during plasma generation, monomers such as CF and CF₂ are produced. When these monomers are deposited onto the silicon surface, polymerization occurs, resulting in the formation of a protective polymer layer over the sample. The vertically incoming ions effectively remove this polymer layer from the horizontal surface, while the sidewalls remain covered. These dual mechanisms enable the creation of vertical profiles in the etching process.

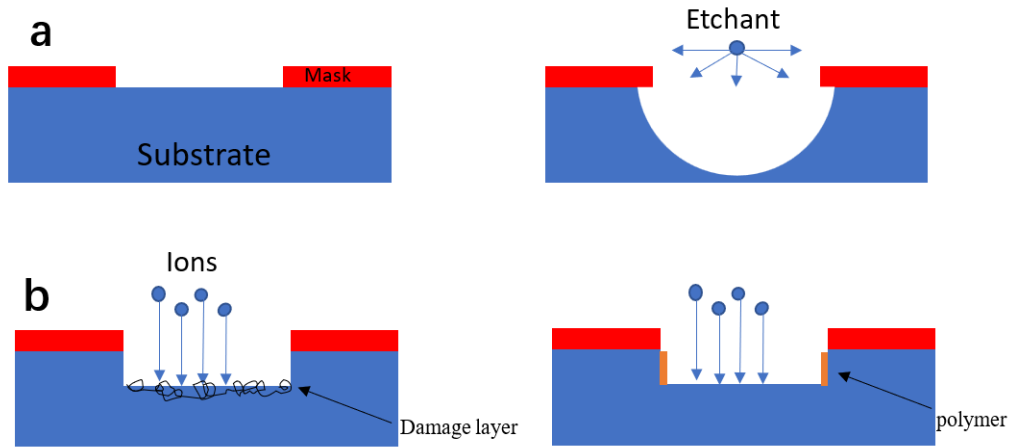


Figure 2.6. Etching profile for (a) wet etching and (b) dry etching (ICP-RIE).

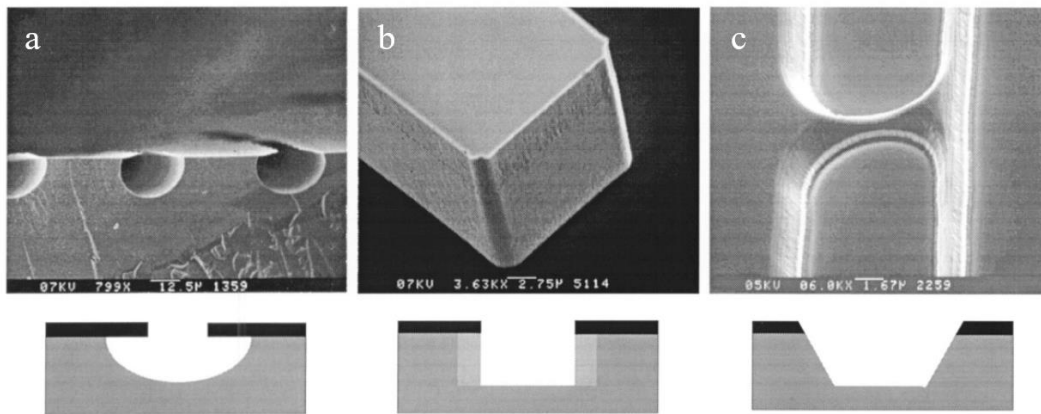


Figure 2.7. Typical etching profiles of the three dry etching processes⁹⁷. (a) the chemical plasma etching (PE), (b) the reactive ion etching (RIE), and (c) the physical ion beam etching (IBE).

For the metalens material, we chose a-Si, which requires a reliable and high-quality etching process on Si. The Bosch process, which uses C_4F_8 and SF_6 to alternate polymerization and etching, is currently the most popular recipe for etching Si⁹⁸. Figure 2.8a depicts the process mechanism for introducing alternative passivation and etching gases. During deposition, a thin Teflon-like film is deposited on both the top surface and side walls. In the subsequent etching step, this film and the underlying Si are etched away from the bottom of the trench. These two steps are repeated until the desired etching depth is achieved, resulting in a typical “scroll” structure in a Bosch process

(Figure 2.8b)⁹⁹.

To eliminate the “scroll” structure, the non-switching mixed gas process has been developed, wherein both SF_6 and C_4F_8 gases are introduced into the chamber simultaneously. In contrast to the sequential introduction used in the standard Bosch process, SF_6 is employed for etching silicon, while C_4F_8 is used to deposit a chemically inert passivation layer concurrently. This innovative process allows for the adjustment of the sidewall taper angle to achieve either a positively or negatively tapered sidewall profile by varying the gas flow ratio of SF_6 to C_4F_8 . Compared to the standard Bosch process, the non-switching mixed gas method presents significant advantages in controlling process parameters, enhancing sidewall profile accuracy, and reducing equipment costs. This approach yields high-aspect-ratio (HAR) nanostructures with smooth sidewalls, making it particularly well-suited for fabricating HAR meta-atoms.

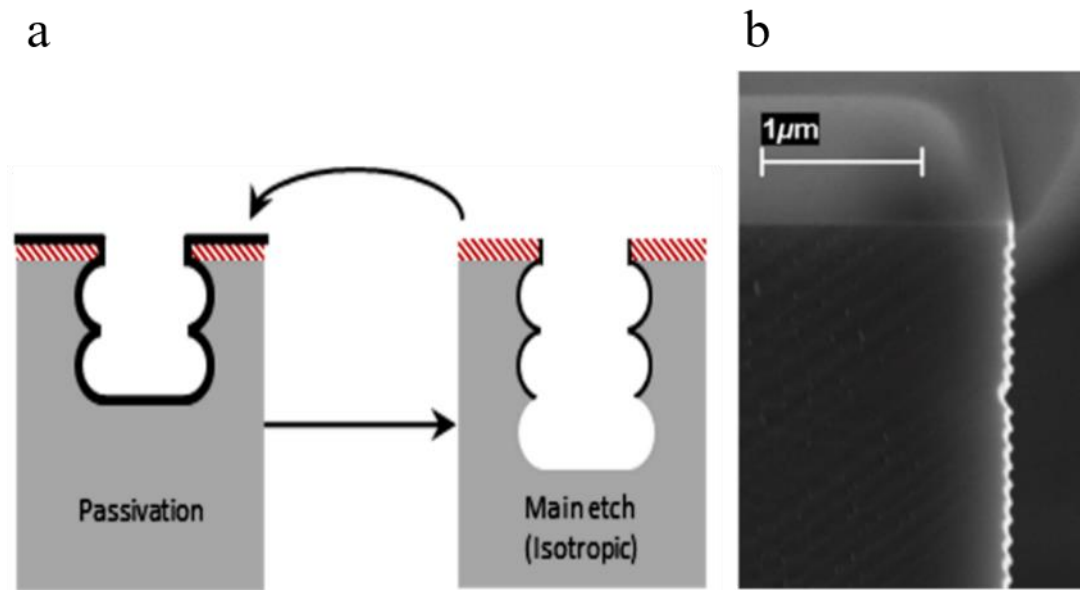


Figure 2.8. Bosch process to etch Si. (a) Basic mechanism of the Bosch process⁹⁸; (b) A typical sidewall structure in the Bosch process⁹⁹.

2.3 NIL-based fabrication

One of the primary challenges associated with EBL is its long exposure time, which can lead to slow processing speeds. To address this issue, NIL^{100,101} has been developed as an alternative. This technique is a high-resolution nanopatterning method that is often used in the creation of nanoscale structures. The process involves transferring patterns from a template onto a substrate material, typically a polymer, using mechanical deformation and replication. Figure 2.9a provides an overview of the typical process flow involved in NIL, which includes template preparation, substrate coating, stamping, demolding, and etching. Dirdal et al. have recently utilized UV NIL in conjunction with Bosch Deep Reactive Ion Etching to fabricate dielectric metalenses, as shown in Figure 2.9b¹⁰². The efficiency of these metalenses was evaluated at 1.55 μm and 1.31 μm wavelengths, resulting in an efficiency of 25.5% and 29.2%, respectively. Compared to traditional lithographic techniques, NIL offers numerous advantages, such as low cost and the ability to pattern large areas with high throughput. It allows for creating complex structures at the nanoscale with uniformity and repeatability. However, it's worth noting that creating the template still requires EBL and must be handled carefully to avoid damage. Moreover, a clean mold-sample separation becomes challenging when imprinting high aspect ratio ($>\sim 5$) structures, which is often the case for meta-lens.

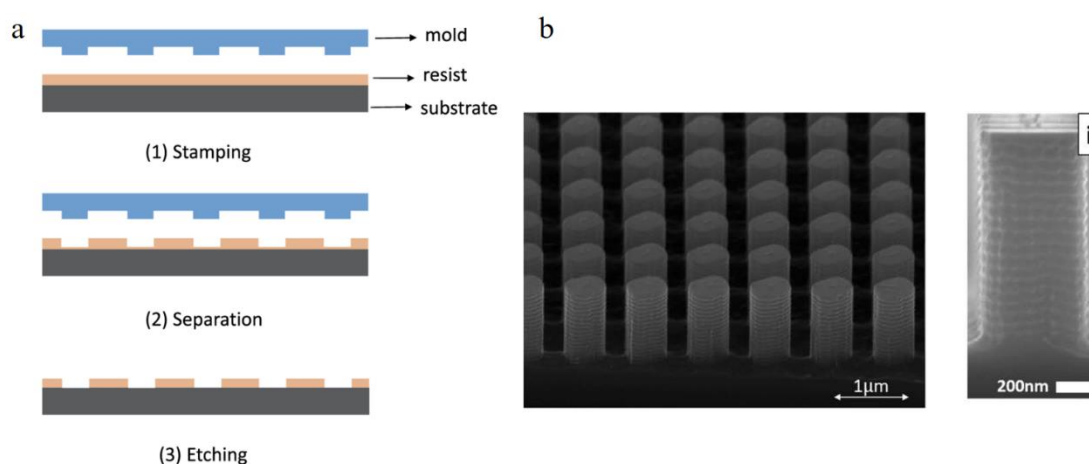


Figure 2.9. NIL process. (a) Process flow of the typical process. (b) Patterned silicon after the Bosch process with imprinted resist¹⁰².

2.4 Lithography-deposition-based fabrication

In contrast to the lithography-etching technique, the lithography-deposition method first applies lithography to the substrate before growing the metasurface material. Rather than etching, the material is deposited into the resist's opening volume. Following back-etching of the over-coated material, the resist is removed, leaving only the desired structure. Figure 2.10 illustrates the entirety of this process flow. This strategy is particularly effective for materials that are difficult to etch and require high-aspect-ratio structures. The research conducted by Zhang and colleagues resulted in the development of high-performance HfO_2 metalenses capable of operating across a wide UV range through lithography-deposition techniques²⁴. HfO_2 is a material that is typically patterned through non-directional wet chemical etching, which makes it challenging to achieve a vertical, high-aspect-ratio etching profile. To address this issue, the researchers utilized atomic layer deposition (ALD) to grow HfO_2 and fill the resist template. Figure 2.11 displays the HfO_2 pillars, which ranged in height from 400 nm to 550 nm and possessed aspect ratios varying from 3 to 11.

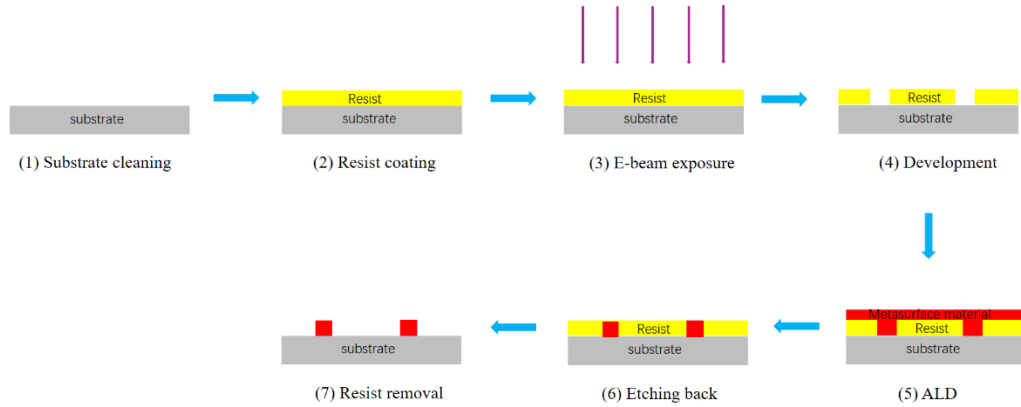


Figure 2.10. Process flow of the lithography-deposition-based fabrication.

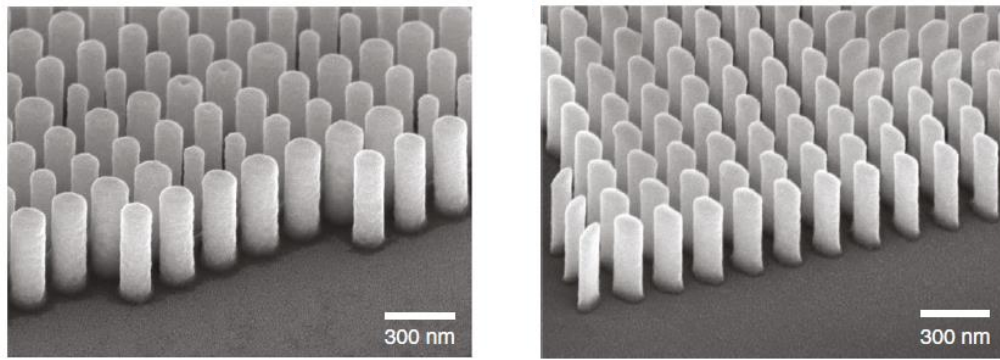


Figure 2.11. SEM images of HfO₂ metalens²⁴.

2.5 3D printing

Earlier methods focused on planar fabrication, making it challenging to develop multilayer structures. In contrast, 3D printing enables the direct creation of multilayered meta-optical components, allowing for detailed phase profile modulation across a broad bandwidth. By combining inverse design with topology optimization, these additive techniques effectively address conventional planar fabrication's limitations, including limited design flexibility and high production costs. Varapnickas et al. utilized femtosecond laser 3D printing technology to design, fabricate, and evaluate dielectric metasurface birefringent optical retarders¹⁰³. This retarder exhibits exceptional polarization conversion efficiency, owing to the versatility of 3D printing technology.

3D printing is increasingly utilized to create metalenses at the tips of optical fibers. These fiber-tip lenses are widely employed in applications such as optical endoscopes and in transmitters and receivers. The traditional manufacturing process for these lenses tends to be quite complex. However, Asa et al. have researched a fiber-tip metalens that is produced using a more straightforward 3D printing method, which is capable of achieving optical trapping of nanoparticles¹⁰⁴. Additionally, Hadibrata and his team demonstrated an inversely designed metalens integrated with a single-mode optical

fiber by 3D printing, with a focal length of approximately $8\ \mu\text{m}$ at a wavelength of $980\ \text{nm}$ and achieving a NA of 0.85. (shown in Figure 2.12)³⁰. This metalens has potential applications in direct laser lithography systems.

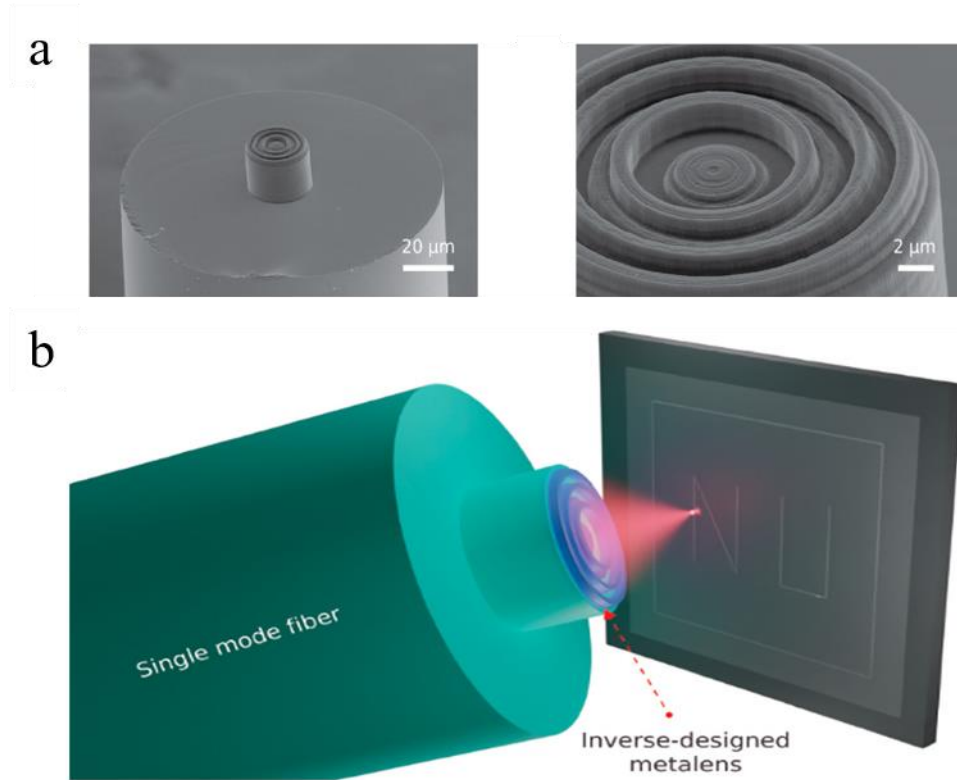


Figure 2.12. Fiber-tip metalens fabricated by 3D printing³⁰. (a) Scanning electron microscopy image of the produced fiber-tip metalens on a single-mode fiber. (b) Schematic of the fiber-tip metalens utilized in the laser direct writing system.

Table 2.1 summarizes the fabrication techniques for metalenses for easy comprehension and reference.

Table 2.1. Summary of different fabrication methods

Methods	Advantages	Disadvantages
Photolithography-etching	Mature process.	Low resolution for normal equipment.
E-beam lithography-etching	High resolution.	High cost and time-

	Flexible in pattern design.	consuming.
Nano-imprinting	Fast replication.	Expensive template. Difficult for high aspect ratio structures.
Lithography-deposition	Suitable for materials that are hard to etch.	ALD is time-consuming.
3D printing	Flexible in design. Can create multilayer structures	Limited material selection.

Chapter 3: Assessment of the Impact of Fabrication Defects on the Optical Performance of Dielectric Metalenses

This chapter involves a unique experimental analysis using real-fabricated devices to investigate the impact of different defects on metalenses, including sidewall angle, uniform critical dimension bias, non-uniform bias due to proximity effect, and pillar missing, on parameters such as focal spot intensity, focal length, and Strehl ratio. This study reveals the significance of precise process control and offers recommendations for time and cost savings.

3.1 Background and Motivations

Metalenses, flat lenses composed of artificial atoms that manipulate the shape of the wavefront based on the generalized Snell's law, have vast potential in various applications. They use abrupt changes in optical properties achieved through precise tuning of materials and parameters within individual unit cells, such as metallic (plasmonic) or dielectric nanostructures. Metallic materials have first been used to create metalens, such as the dual-polarity metalens fabricated by Chen et al. using Au and operating in the visible region¹². However, the efficiency of these metalenses is restricted due to the high ohmic loss associated with metallic materials^{13,14}. In contrast, dielectric materials such as Si, Si₃N₄, TiO₂, and HfO₂ are currently garnering more attention.

In the context of metalens fabrication, metalens composed of the aforementioned materials are commonly implemented using two typical approaches: film deposition followed by etching, and the Damascene lithography. Both processes tend to introduce

similar types of defects—such as inclined sidewall angles, uniform critical dimension (CD) bias, non-uniform CD bias, and missing pillars—which can greatly affect both the yield and optical performance of the finished product. Some studies focusing on the metalens with process defects are reported^{106,107}. However, these progresses have been made through simulations, and experimental investigations on the optical performances of metalenses with process-induced defects have not been reported yet. As a result, a comprehensive and systematic investigation of these defects, integrating simulations and experiments, has become a critical aspect of metalens production. By better understanding the mechanisms behind process-induced defects, we can develop more effective strategies to minimize their impact and improve the quality of metalenses.

presents our investigation of dielectric metalenses, covering common fabrication processes and potential defects, such as inclined sidewall angle, uniform critical dimension (CD) bias, non-uniform CD bias due to the proximity effect, and pillar missing due to the notching effect. To characterize the optical performance of the metalenses, we conducted measurements and calculations of focal spot intensity, focal length, and Strehl ratio (SR). We specifically select metalenses fabricated from amorphous silicon (a-Si) on a fused silica substrate, targeting a wavelength of 940 nm for our research. This choice is based on the maturity of silicon's fabrication methods and the ease with which we can deliberately introduce defects in its profile. Our systematic research underscores the importance of understanding and addressing process-induced defects in the fabrication of metalenses.

3.2 Metalens design

This section explains how we create a metalens from the ground up, and the types of defects we selected.

3.2.1 Design of the reference metalens

Phase modulation methods of metalenses are typically based on the resonant, propagation, or geometric phase⁹⁶. In this work, we used the propagation phase to control the wavefront, as it offers greater universality and broader applicability. The whole metalens consists of thousands of unit square-shaped cells, each containing one nanopillar. The transmission phase can be manipulated by adjusting the radius of nanopillars, which affects the effective refractive index. The necessary phase profile for a focusing metalens is determined by:

$$\phi(x, y) = -\frac{2\pi}{\lambda}(\sqrt{x^2 + y^2 + f^2} - f) \quad (12)$$

Where λ and f represent the wavelength and focal length, and x and y are the coordinate positions on the metalens. The commercial FDTD simulation software Ansys Lumerical is used to design the structure. Our metalens design involved the use of amorphous Si (a-Si) nanopillars on a silicon dioxide (SiO₂) glass substrate. The refractive indices n of a-Si and SiO₂ are 3.0 and 1.47 at $\lambda = 940$ nm, respectively, based on the results of ellipsometry measurements.

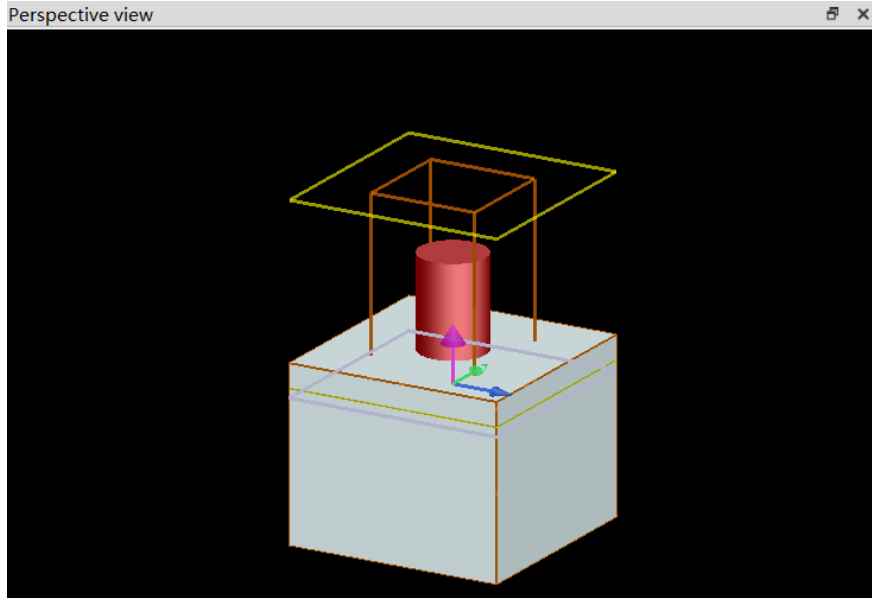


Figure 3.1. 3D view of a unit cell as designed in Lumerical FDTD.

To begin the design process, we first need to gather data on the phase shift and

transmission changes that occur with varying pillar radii. Using Lumerical FDTD, we simulated a unit cell (shown in Figure 3.1). We created a library of phases based on nanorod radius to achieve a 2π phase change across the radius range we're considering. This library will be a mapping tool for placing nanopillars with the desired phase at each metalens grid point. Additionally, we conducted a sweep of the nanopillar height to identify the optimal value for achieving maximum transmission. Figure 3.2 presents 2D maps that illustrate the phase and transmission in relation to the height and radius of the pillar. The transmission maintains an exceptionally high level throughout the entire radius below 800 nm. Notably, the phase experiences significant changes within the given radius range (0.05 - 0.18 μm), with differences larger than 2π observed for height values of 690 nm or higher. To conclude, Table 3.1 lists the final parameters that we have selected.

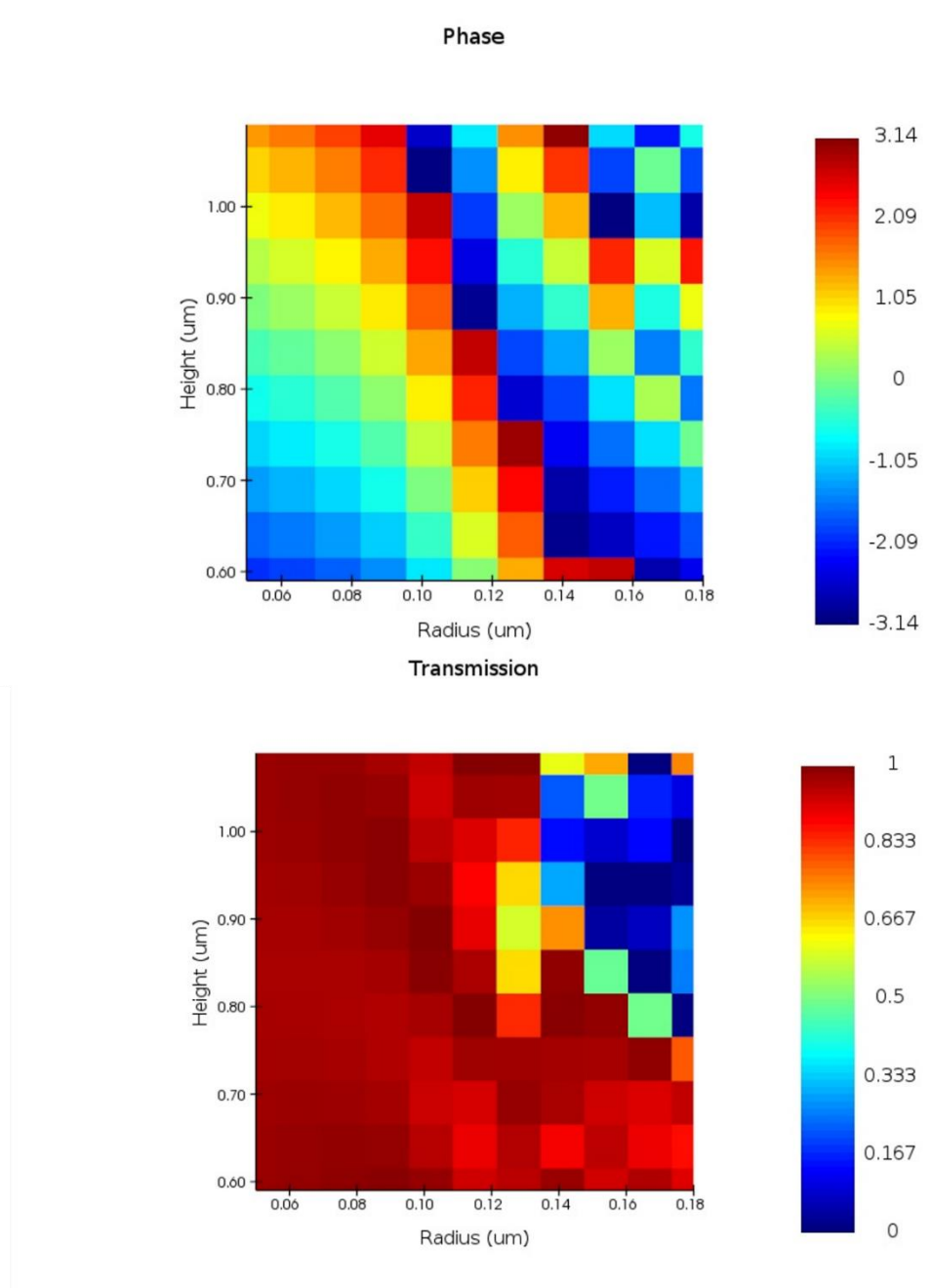


Figure 3.2. 2D maps of the phase and transmission in terms of the height and radius of the pillar.

Table 3.1 Parameters of the unit cell simulation

Pillar height	750 nm
Pillar radius	104 – 338 nm
Pillar pitch	480 nm

Lens diameter	200 μm
Focal length	380 μm
Working wavelength	940 nm

Figure 3.3 shows the phase-diameter and transmission-diameter curves. A 2π phase shift is achieved within this range, and the transmission reaches as high as 0.9.

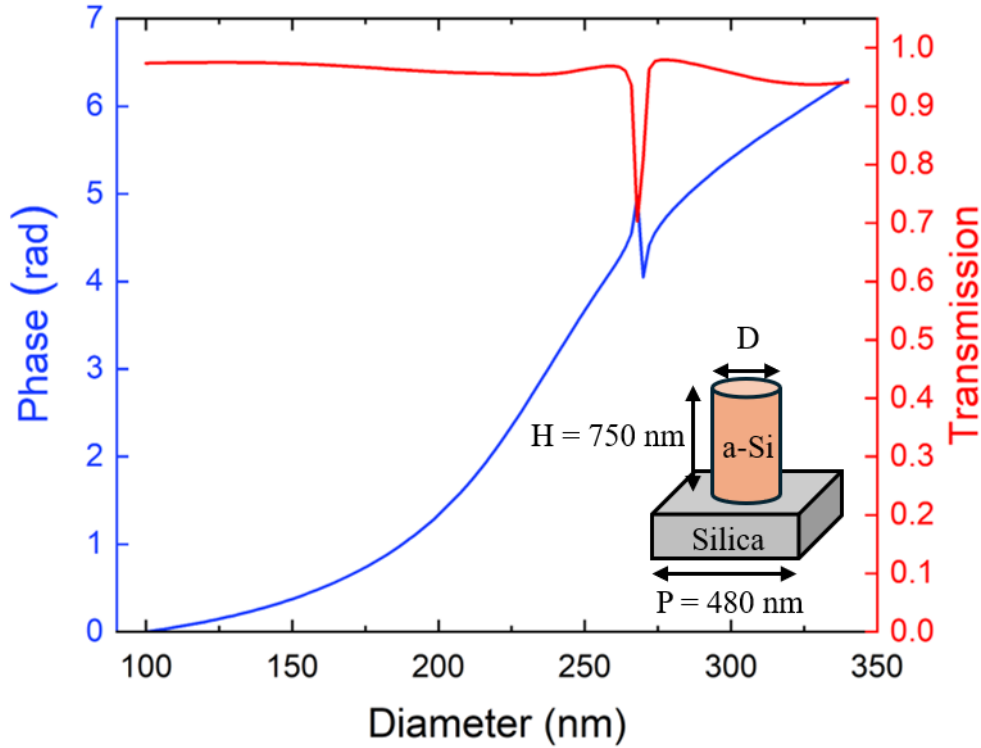


Figure 3.3. Phase shift and transmission with the change of pillar diameter.

The next step involved creating the full lens by converting the spatial phase profile into a spatial radius distribution of nanopillars, as shown in Figure 3.4. The target phase map was generated according to equation (12). This process was again conducted using Lumerical FDTD software. The full lens has a diameter of 200 μm and a focal length of 380 μm . The phase map of the full lens and its modeling in Lumerical FDTD are illustrated in Figures 3.5a and b.

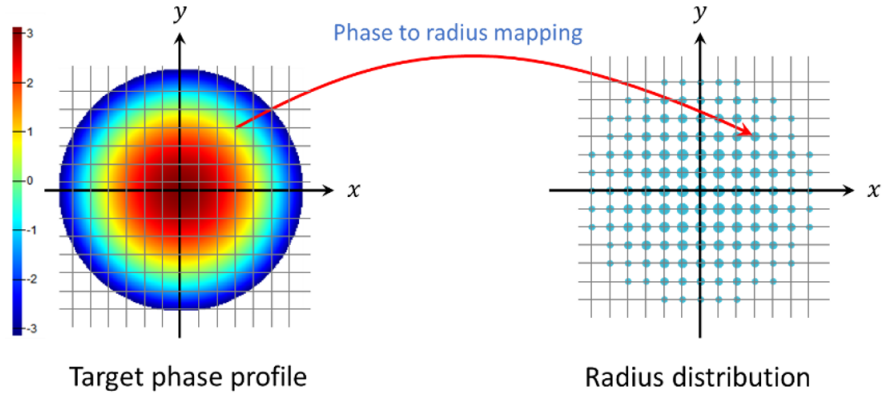


Figure 3.4. Example of the phase-to-radius translation¹⁰⁸.

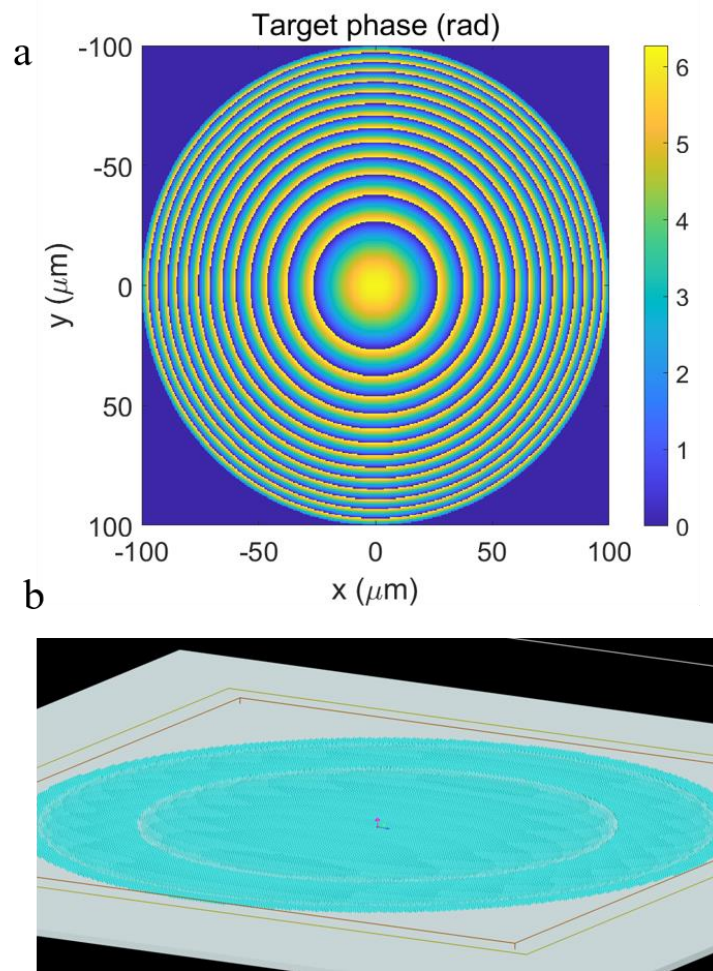


Figure 3.5. (a) Phase map of the full lens. (b) 3D view of the full lens as designed in Lumerical FDTD.

Figure 3.6 displays the results of the far-field projection analysis. The lens exhibited good focusing capabilities, as evidenced by the x-y plane focal plane profile. The

beam's FWHM at the focal plane is approximately 5 μm . The profile along the propagation axis (z) indicates that the lens's focal depth is 380 μm . After the simulation, a gds file was exported for the following fabrication process.

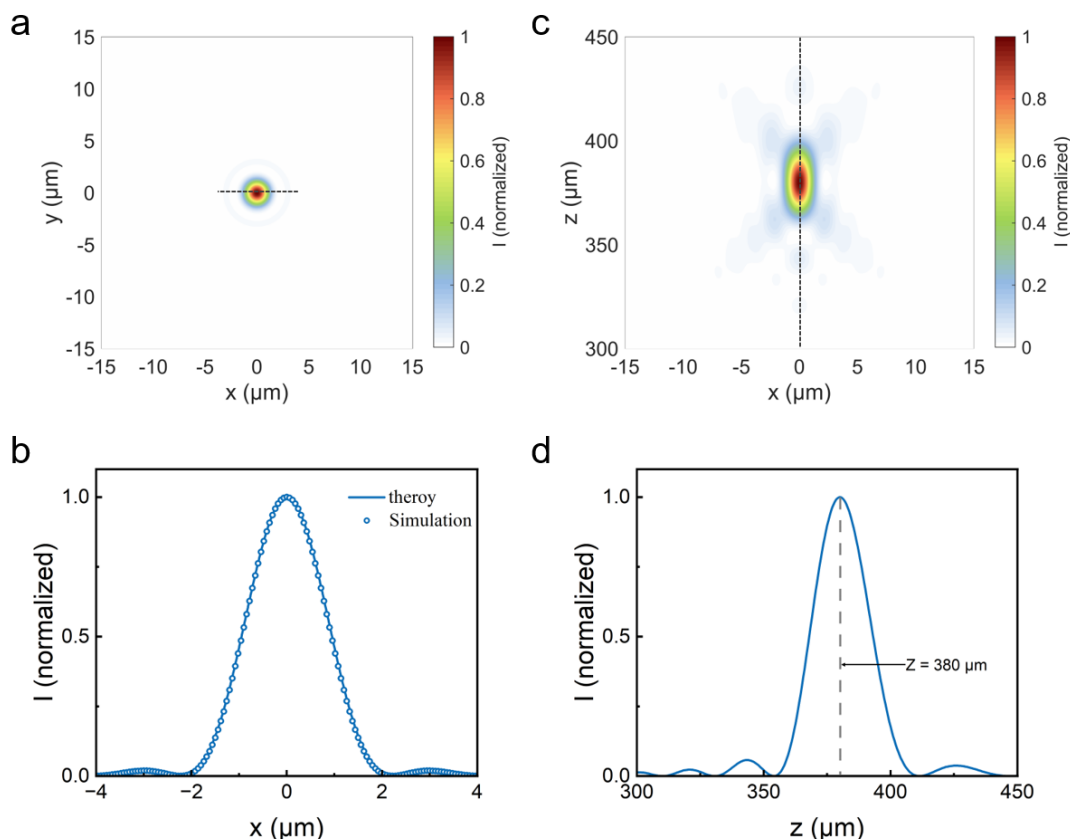


Figure 3.6. (a) Simulation results of focal plane profiles in the x-y plane. (b) cross-sectional profiles of the focal spots in the x-y plane. (c) Simulation results and theoretical prediction of focal plane profiles in the x-z plane. (d) cross-sectional profiles of the focal spots in the x-z plane. Dashed line: focal length.

3.2.2 Defect design

There are two widely utilized methods for fabricating dielectric metalenses. One method involves e-beam lithography combined with dry etching, which we selected to fabricate our a-Si metalenses. The second technique, known as Damascene photolithography, also employs e-beam lithography to create a resist template, which is subsequently filled with dielectric materials using atomic layer deposition (ALD). Following the etching back and removal of the resist, nanostructures are generated.

Unlike the first method, this technique does not involve dry etching, but it still requires lithography. Our investigation analyzed four imperfections that commonly arise in the techniques mentioned above: inclined sidewall angle (SA), uniform CD bias, non-uniform CD bias, and pillar missing. These are listed in Table 1.

Table 3.2 Summary of all defects

Sample #	Sidewall angle	Uniform CD bias	Non-uniform CD bias	Pillar missing
1(Reference)	90°	0	No	No
2-6	86° - 91°	0	No	No
7-12	90°	-30 – 30 nm	No	No
13-17	90°	0	Yes	No
18	90°	0	No	Yes

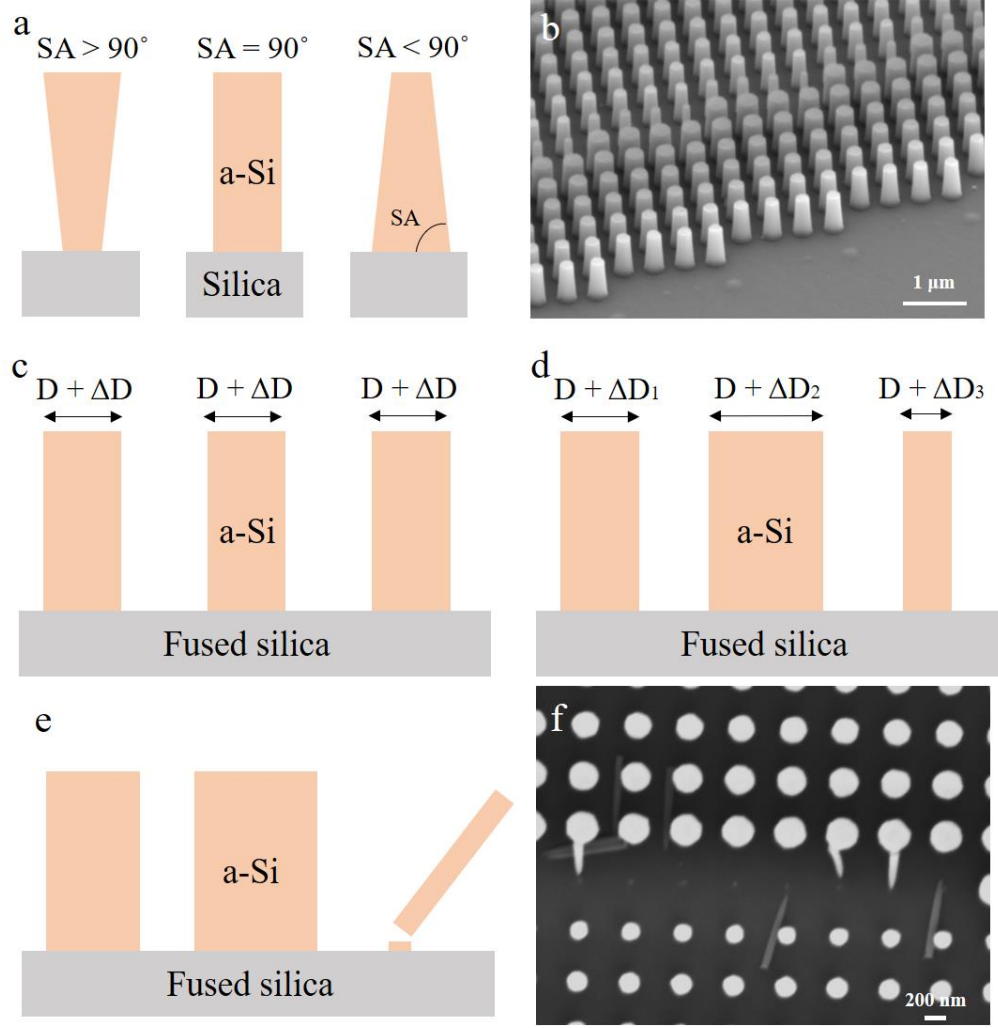


Figure 3.7. Schematics of defects. (a-b) Sidewall angle. (c) Uniform CD bias. (d) Non-uniform CD bias. (e-f) Pillar missing.

Figures 3.7a and b display imperfect profiles exhibiting positive or negative tapering during Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE). Our simulation assumes a perfectly vertical etching profile, but this is highly unlikely in reality. We must carefully fine-tune the etching recipe to achieve a near-vertical profile. However, imperfect profiles with positive or negative tapering are common in practice. The SA is defined as the angle between the substrate surface and the sidewall of nanopillars, as illustrated in Figure 3.7a. The reported simulation works indicate that the focusing intensity decreases by approximately 3.6% for every +1 degree¹⁰⁶. This reduction is

significant and valuable for further experimental study. To evaluate the effects of these angles, we will create various samples with SAs ranging from 86° to 91° . It's important to note that SA cannot be too large, as it may lead to structural collapse.

There are two types of bias: uniform bias, arising from inappropriate lithography parameters (such as dose and development time), and non-uniform bias, resulting from the proximity effect of e-beam lithography. Figure 3.7c illustrates the consistent deviation in feature size from the intended design, which often occurs in lithography due to inappropriate exposure dose and developing time. Figure 3.7d illustrates the non-uniform size variation caused by the proximity effect in e-beam lithography. This effect introduces different biases to structures with varying coordinates and sizes¹⁰⁹, which can be minimized through a proximity effect correction (PEC) process¹¹⁰.

The proximity effect in e-beam lithography can cause non-uniform biases, leading to central patterns becoming larger and outer patterns becoming smaller¹⁰⁹. During e-beam lithography, a resist layer on a substrate is typically patterned by directly exposing the sample with a focused electron beam. However, this process results in the scattering of primary electrons in both the resist layer (forward-scattered electrons, FE) and the substrate material beneath (backscattered electrons, BE). As a result, secondary electrons (SE1 and SE2) are created during the scattering process, which contributes to the total exposure dose at all substrate regions (as shown in Figure 3.8)¹¹¹. This can lead to adjacent regions receiving a higher total electron dose than intended, resulting in an imprecise implementation of the designed pattern on the sample with respect to both shape and location. In a typical metalens design, patterns in the central area will receive a higher dose while the outer area receives a lower dose. To ensure maximum pattern fidelity, it's important to compensate for the proximity effect by adjusting the initial electron dose distribution in the design. This is known as the proximity effect correction

(PEC)¹¹⁰ and involves comprehensive and computationally intensive processing. The goal of PEC is to ensure that every point in the design receives the same electron dose. At our QNF lab, we use the commercial software GenISys GmbH Layout BEAMER to apply PEC and achieve optimal results.

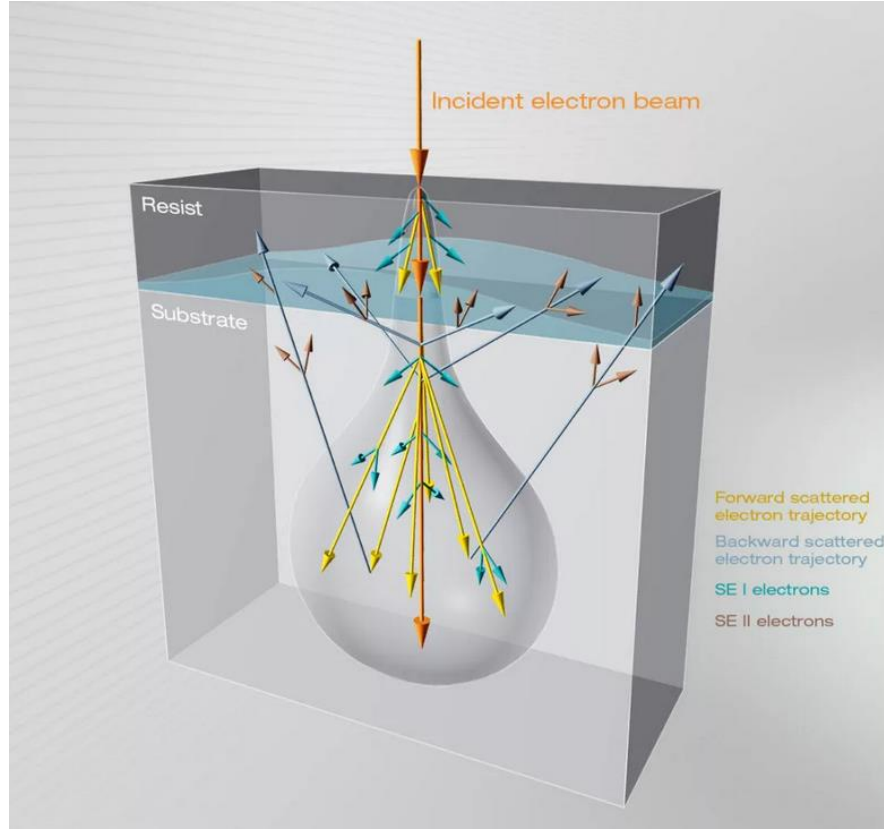


Figure 3.8. Simulation of electron trajectories resulting in a double Gaussian distribution, causing the proximity effect¹¹¹.

Displayed in Figure 3.9 is a metalens configuration featuring a 2.8 μm pillar pitch and 2.4 μm pillar dimension, with and without PEC. The figures demonstrate that in the absence of PEC (Figure 3.9a), the central pattern received a significantly larger dose and exhibited an increased dimension. In contrast, the pattern with PEC (Figure 3.9b) demonstrates consistent accuracy in structure size throughout the area. Figure 3.10 shows another metalens design with a significantly smaller pitch and pillar size, measuring in the hundreds of nanometers. Notably, this result was not optimized with

PEC. We selected two rectangles and measured their dimensions at both the center (a) and edge (b). Interestingly, the structure size at the center demonstrated a 10 nm increase compared to that at the edge. Although the influence of the proximity effect is still observable, the size difference between locations is less pronounced than in the previous result. This may be due to the much smaller exposure area relative to the entire pattern area (i.e., smaller filling ratio), resulting in a smaller proximity effect. That is, patterns at the center does not receive a significant dose from adjacent patterns, resulting in a weaker impact of the proximity effect. The pillar dimensions of our metalens vary from 104 to 338 nm, where the proximity effect might not be very significant. It's essential to determine whether it's the primary factor.

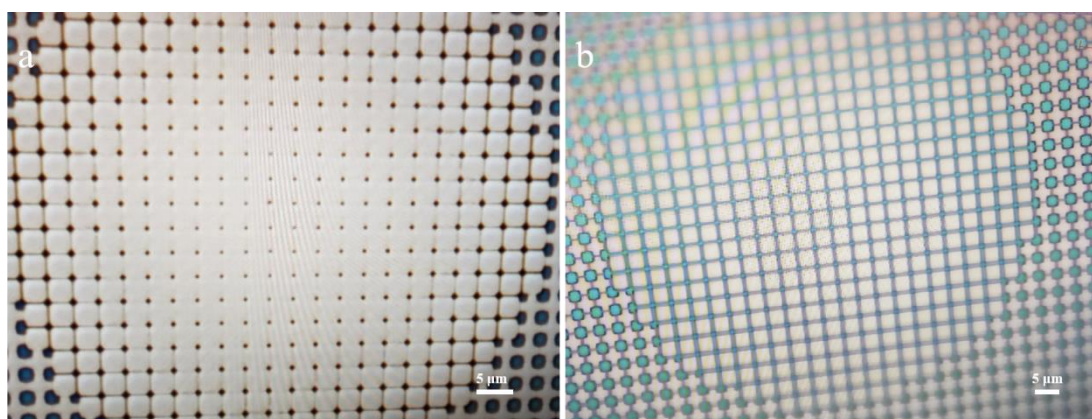


Figure 3.9. Patterns without PEC (a) and with PEC (b). The white area was exposed and removed after EBL and development.

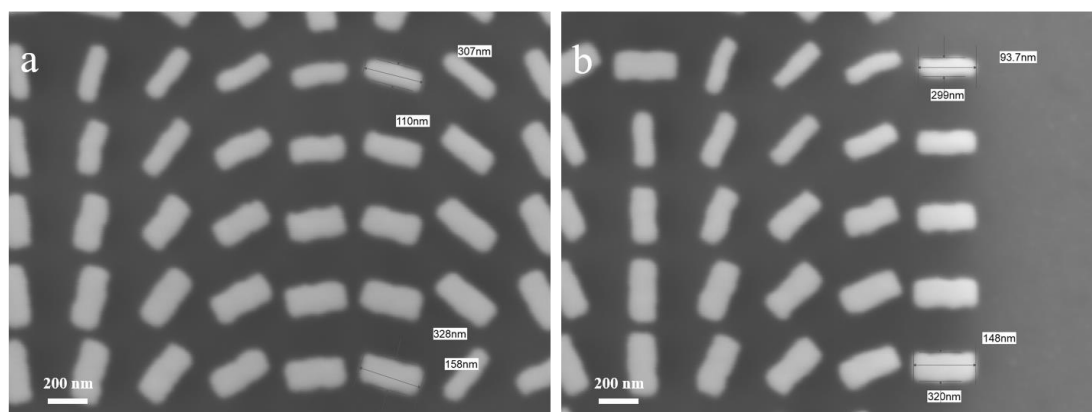


Figure 3.10. SEM images of structures at the center (a) and at edge (b) without PEC.

Lastly, Figures 3.7e and f demonstrate the absence of pillars. In dry etching, this can arise from the notching effect¹¹². This issue leads to increased lateral etching at the lower part of the structure, potentially compromising the connection with the substrate, which is a result of charge accumulation on the bottom surface^{113,114}. This effect becomes more pronounced when an insulating substrate is used that cannot quickly dissipate the accumulated positive charges caused by positive ion bombardment onto the surface. In the case of the lithography-deposition process, this issue may occur from the challenges associated with filling the template at high aspect ratios. In both scenarios, smaller pillars are at a greater risk of collapse compared to the random loss of pillars. In the case of damascene photolithography, this issue may occur from the challenges associated with filling the template at high aspect ratios. In both scenarios, smaller pillars are at a greater risk of collapse compared to the random loss of pillars.

3.3 Experiments

3.3.1 Fabrication Process Flow

The whole fabrication process is outlined in Figure 3.11. To start, a fused silica wafer was thoroughly cleaned with acetone and IPA, followed by oxygen plasma cleaning (RF: 20 W; O₂: 20 sccm, 20 mTorr, 2 minutes). Next, a 750 nm a-Si layer is deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD). An e-beam resist ZEP520A is then spin-coated onto the a-Si, which is subsequently exposed to a pattern area using e-beam lithography (JEOL FS-6300) at 100 kV. After development using N50 developer, a 15 nm Cr₂O₃ layer is deposited using e-beam evaporation. The sample is then subjected to a lift-off process in PG remover at 80 °C for 30 minutes. The pattern is transferred into a-Si using Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE) with specific etching recipes (will be discussed in Chapter 4). Finally, the remaining hard mask is removed by dipping the sample into Cr etchant and rinsing it with DI water.

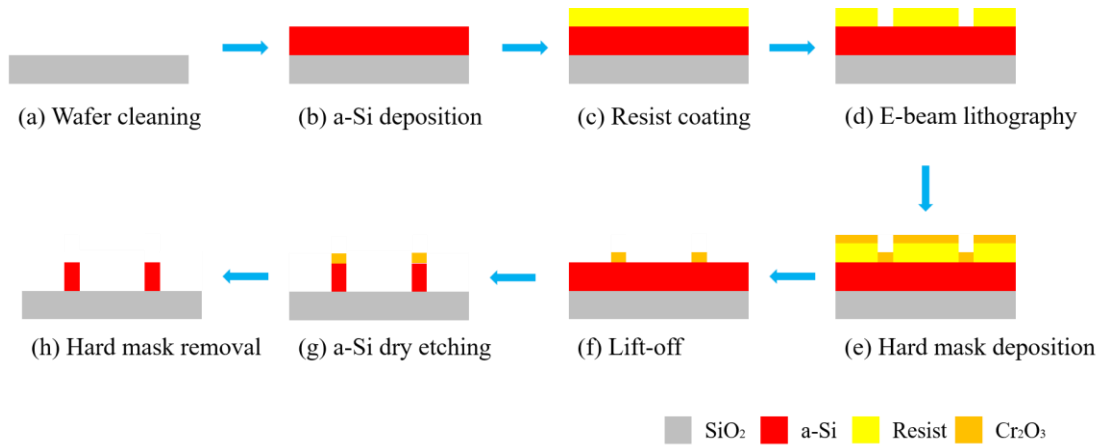


Figure 3.11. Process flow of metalens fabrication.

3.3.2 Nanopillar material deposition

Currently, a variety of dielectric materials are widely utilized in metalenses, including a-Si and TiO₂. In our experiments, we chose a-Si as the material for the nanopillars due to its well-established deposition and etching procedures, which are available at Quantum Nano Fab (QNF). The deposition of a-Si was performed using Plasma-Enhanced Chemical Vapor Deposition (PECVD), preceded by the in-situ deposition of a 50 nm SiO₂ layer to improve adhesion of a-Si to the glass substrate. After deposition, we used an ellipsometer to measure both the film thickness and refractive index, as illustrated in Figure 3.12, which shows the measurements of refractive indices of a-Si and SiO₂ across varying wavelengths. Importantly, the mean squared error (MSE, given by the ellipsometer) was recorded at just 7, indicative of highly accurate data acquisition and fitting. According to our measurements, the refractive index of a-Si at a wavelength of 940 nm was approximately 3.0. Additionally, we carefully examined the film thickness of all 16 samples listed in Table 3.2, and the results are shown in Table 3.3. It's crucial to understand that metalenses free of defects (#1), those exhibiting a uniform CD bias (#7-12), and those with a non-uniform CD bias (#13-17) all share the same substrate, resulting in equal film thickness for each. The film thickness across

these samples ranged from 740 to 760 nm, demonstrating our precise process control.

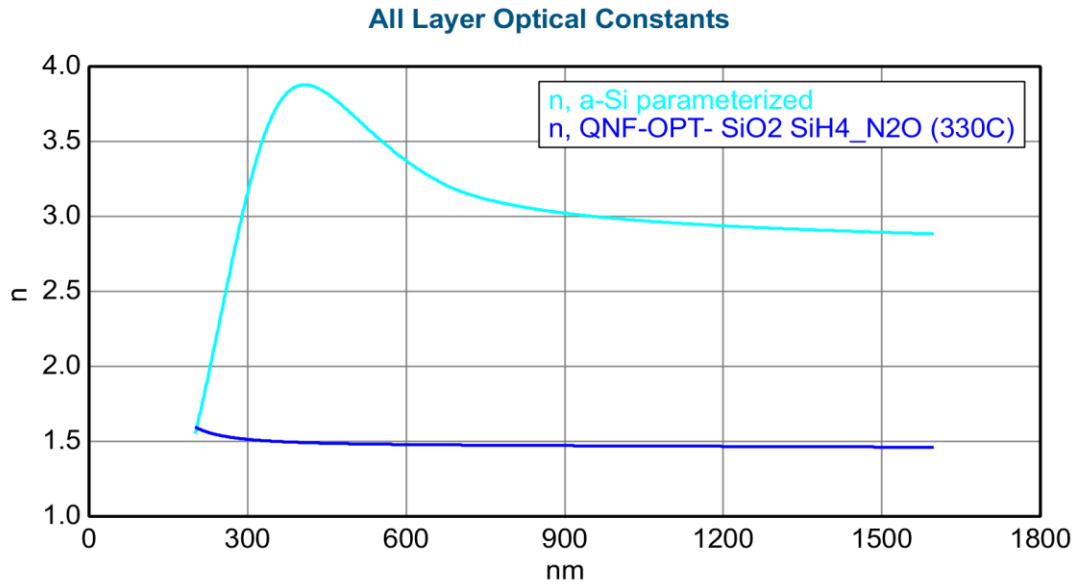


Figure 3.12. A screenshot of the ellipsometer interface and the refractive indexes of our PECVD a-Si and SiO₂.

Table 3.3 Film thickness of all samples

Sample #	Film thickness(nm)	Sample #	Film thickness(nm)
1 (Reference)	750	7-17	750
2	755	5	755
3	758	6	760
4	745	18	753

3.3.3 E-beam lithography

In our experimentation, nanostructures were patterned using e-beam lithography (EBL). Despite its high cost and time-consuming process, EBL boasts the highest resolution when compared to other methods. Moreover, our metalens pattern areas are relatively small, measuring 200 μm , and can be fully exposed within 20 minutes using 4 nA and

100 kV in EBL.

Initially, during our preliminary tests, we spin-coated the e-beam resist onto the insulating a-Si/SiO₂ substrate before conducting EBL. Following the development and lift-off of the chromium (Cr), we observed a disordered pattern, as illustrated in Figure 3.13, which was attributed to charging effects. It's important to note that the test pattern displayed differs from our actual metalens design. Typically, in EBL, the substrate must be a conductor or semiconductor; otherwise, charges cannot be taken away quickly. Due to the accumulation of charges caused by the bombardment of electron beams on the surface of insulating materials, the scanning position of the electron beam will deviate from the designed position on sample surface¹¹⁵. This disruption can lead to large shifts in the pattern by a few micrometers or even by several hundred micrometers, resulting in significant distortion of the exposed patterns. Furthermore, there is a risk of sparking discharge phenomena occurring on the surface of the substrate, damaging both the resist and the substrate surface.

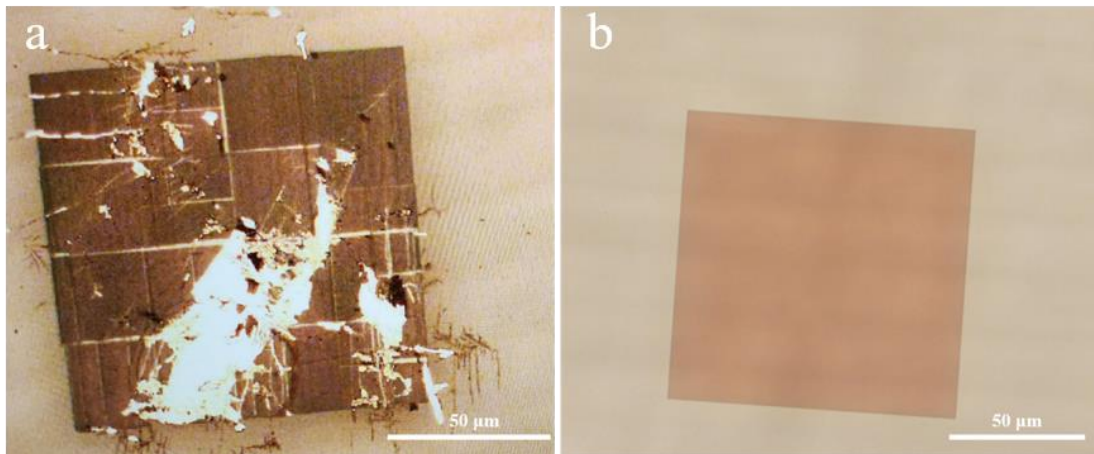


Figure 3.13. (a) Lift-off result with a severe charging effect. (b) Lift-off result with conducting layer applied.

To solve this problem, a 70 nm thick conducting layer was applied directly to the e-beam resist through spin coating. The implementation of Electra-92, a commercially

available conducting layer that uses water and isopropanol as solvents for spin coating, resulted in a significant improvement in EBL performance, as illustrated in Figure 3.13b. Notably, we switched the mask material from Cr to Cr_2O_3 to minimize the etching undercut, resulting in a different color after lift-off. Additionally, this conducting layer can be easily removed with a 1-minute water rinse before the development stage.

3.3.4 Inductively Coupled Plasma-Reactively Ion Etching

Following EBL, we implemented a series of non-switching mixed gas etching processes to produce high-aspect-ratio nanopillars with smooth sidewalls, utilizing a continuous injection of C_4F_8 and SF_6 at a constant gas flow ratio. The gas flow ratio is critical, as it significantly influences the etching profile. We will explore this topic in greater detail in Chapter 4.

3.4 Results and Discussion

3.4.1 Measuring system of optical performance

All lenses listed in Table 3.2 were then measured using a 940 nm laser. The schematic diagram of the metalens testing system is shown in Figure 3.14. A narrow-linewidth laser emitting at 940 nm serves as the light source and is connected to a fiber collimator within the testing system. The focal plane was identified and captured using an objective lens in conjunction with a THORLABS sCMOS camera (CS2100M-USB). Initially, we assessed the reference sample, which was free of defects and demonstrated a SA of 90° , a uniform bias of 0, and no non-uniform bias, achieved through a finely optimized etching recipe that eliminated the notching effect. The focal spot intensity of all samples was normalized to that of the reference sample. To characterize the optical performance of the lenses, we conducted measurements and calculations of focal spot intensity, focal length, and Strehl ratio (SR).

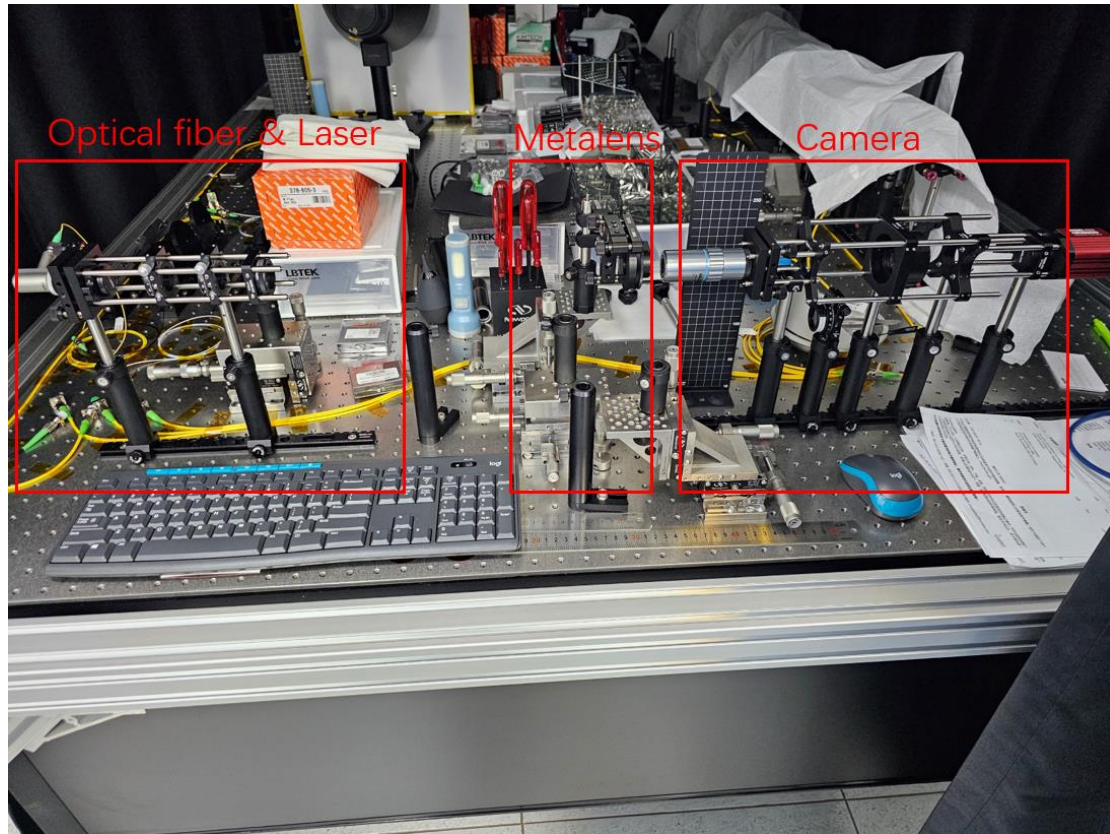


Figure 3.14. Schematic and photograph of the metalens testing system.

3.4.2 Reference metalens

The reference metalens (sample #1) was initially examined using both an optical microscope and a scanning electron microscope (SEM). As illustrated in Figure 3.15a, no defects were detected under the optical microscope. The SEM images, captured from both top and side angles, clearly reveal that all pillars exhibit a well-defined, round shape with smooth, vertical sidewalls. Due to the presence of thousands of pillars on our metalens, it's impossible to specify the dimensions of all of them. To verify the accuracy of the pillar dimensions in relation to our design, we selected two specific pillars at a fixed location—the largest ($D = 338$ nm according to the design) and the smallest ($D = 104$ nm according to the design), as shown in Figure 3.15b. In the fabricated metalens, the largest and smallest pillars measured 340 nm and 103 nm, respectively, resulting in bias (ΔD) values of 2 nm and -1 nm, demonstrating excellent

process control.

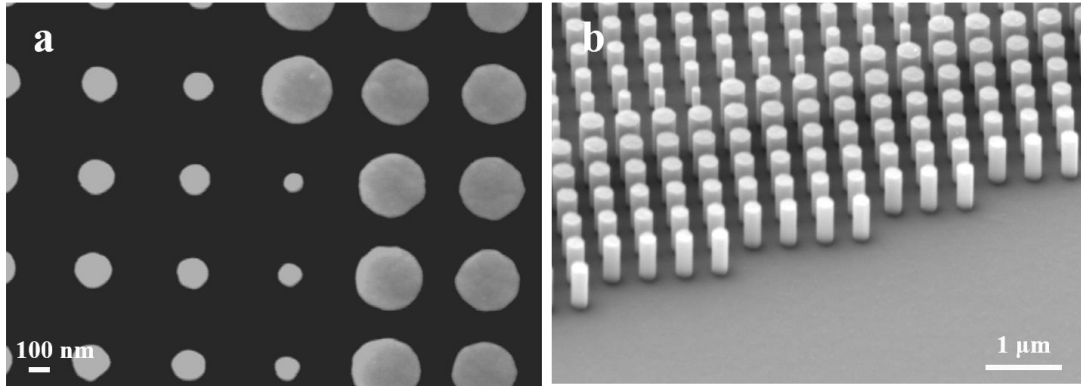


Figure 3.15. (a) Top view and (b) side view of SEM images showing Sample #1 of the metalens, which is the reference.

3.4.3 Inclined sidewall angle

By employing different etching recipes during the Inductively Coupled Plasma-Reactively Ion Etching (ICP-RIE) process, which will be discussed in Chapter 4, we successfully achieved a range of SAs from 86° to 91° , as depicted in the SEM images in Figure 3.16a-f. Additionally, to obtain a more precise measurement of the SA, we utilized tweezers to gently push down the nanopillars and captured top-view images. After measuring the diameters of the top and bottom surfaces, we could calculate the SA. As illustrated in Figures 3.17a-f, all six samples exhibit excellent quality, with SAs that align well with our design specifications.

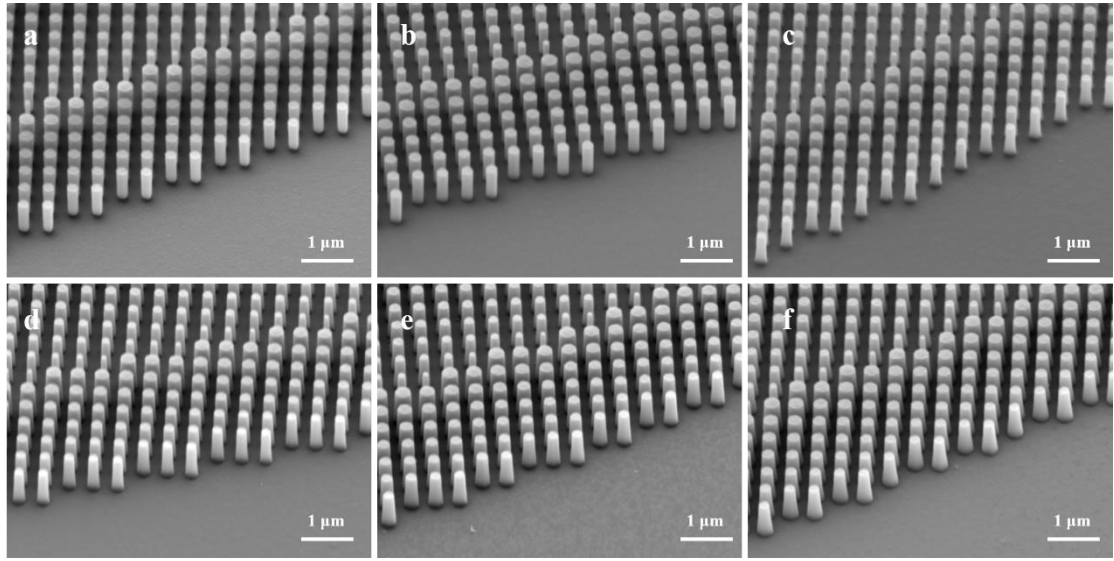


Figure 3.16. SEM images of metalenses with different SAs. (a) SA = 91°. (b) SA = 90°. (c) SA = 89°. (d) SA = 88°. (e) SA = 87°. (f) SA = 86°.

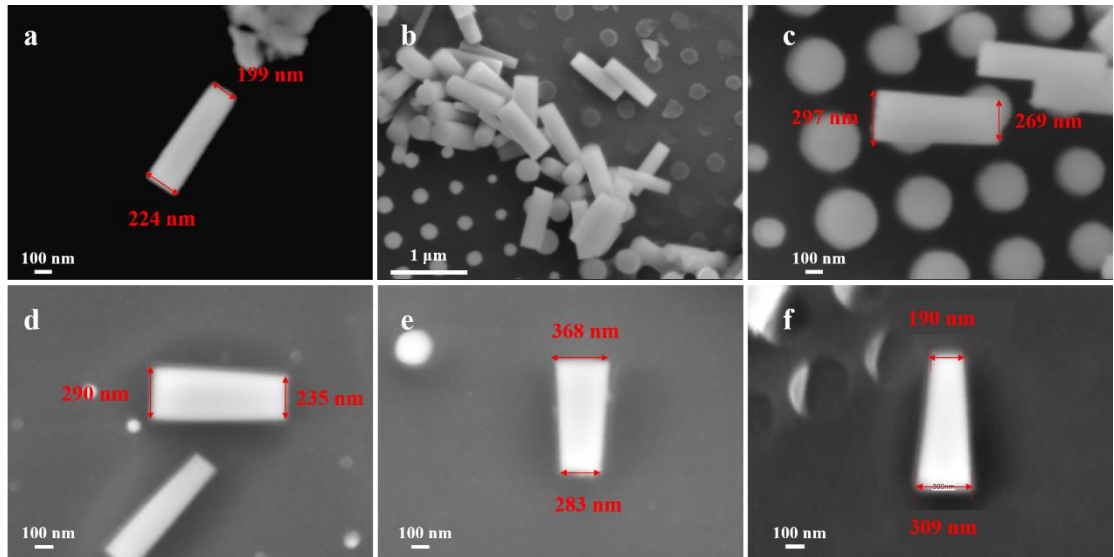


Figure 3.17. Top-view SEM images of nanopyramids pushed down. SA was calculated after measuring the top surface dimension and the bottom surface dimension. (a) SA = 90.96°. (b) SA = 90°. (c) SA = 88.93°. (d) SA = 87.90°. (e) SA = 86.76°. (f) SA = 85.65°.

Figure 3.18 illustrates the normalized focal spot intensity, focal length, and SR of all six samples (#2-6) with different SA, incorporating simulated and experimental data. The results demonstrate that the experimental data align closely with the simulated data, despite some differences in the specific values. Figure 3.18b illustrates the relative peak

intensity of all metalenses, showing a rapid decrease from 100% to 53% as the SA transitions from 90° to 86° . This reveals a nearly linear decline in focusing quality of approximately 11% for each degree of change. At an SA of 91° , the relative intensity drops only by 5%, which is noticeably less significant than the drop at 89° .

The analysis also covers focal length and the SR, as shown in Figures 3.18c-d. It is noted that a negative deviation from 90° in SA results in a slight increase in focal length, whereas a positive deviation leads to a minor decrease. The SR is an important metric for evaluating lens focusing quality. It is defined as the ratio of the area under the modulation transfer function (MTF) to the area under the diffraction-limited MTF¹¹⁶ (as illustrated in Figure 3.18a). The SR values range from 0 to 1, with an ideal lens, characterized by a diffraction-limited focal spot and the intensity distribution of an Airy disk, achieving an SR of 1. A decrease in the SR signifies a decline in focusing quality. All SAs that are not 90° contribute to a reduction in the SR. Specifically, the SR declines from 0.934 to 0.913 as the SA ranges from 90° to 86° . Notably, at 91° , despite its relatively good performance in terms of intensity, this metalens exhibits a significant reduction in the SR; the decrease in the SR at 91° is even more pronounced than that observed at 88° . This difference does not appear in the simulations, likely due to the lower sections of the pillars being attacked more by the ion flow during the dry etching. This makes negatively tapered structures especially susceptible to having a very small footing, leading to an even greater SA ($> 91^\circ$) at the bottom.

The variation in focal spot intensity, focal length, and the SR can be attributed to increased phase errors caused by more tapered sidewalls, which reduce the lens's ability to effectively bend light. Furthermore, the nanopillars in the metalens exhibit a high aspect ratio (ranging from 2 to 7), meaning that even minor changes in SA result in significant performance variations.

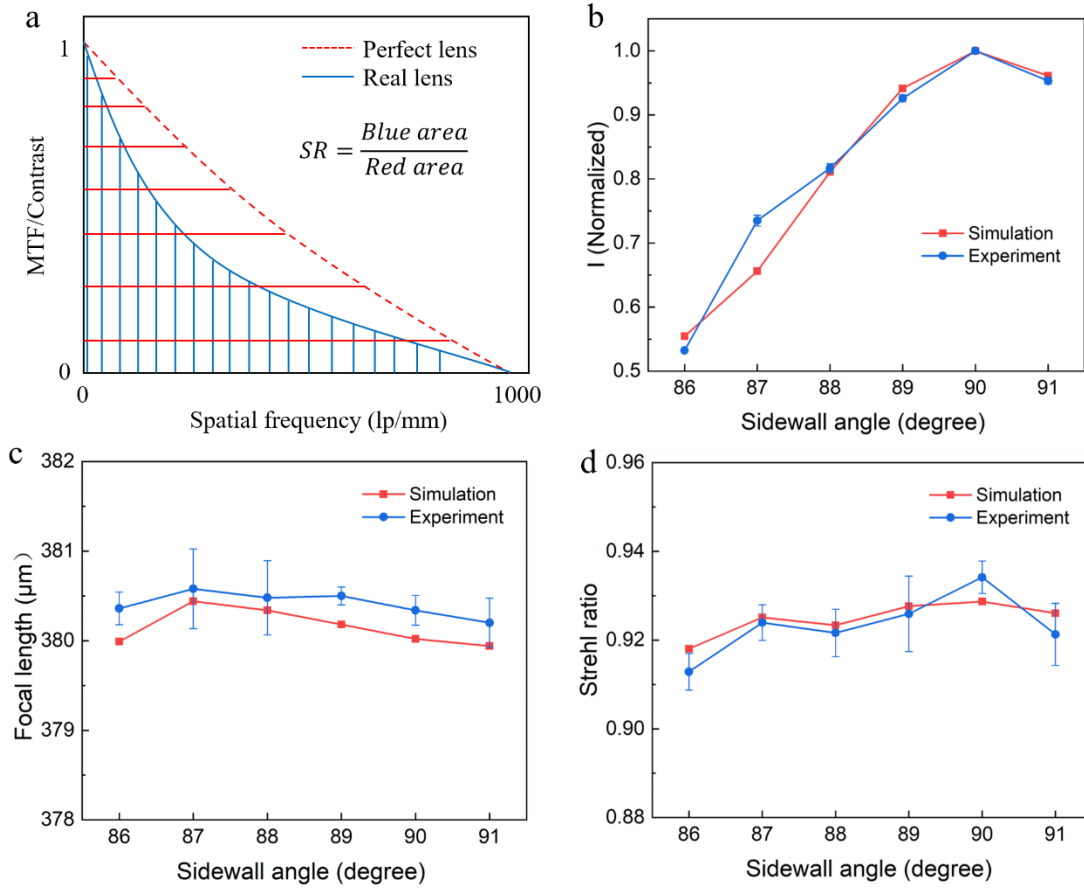


Figure 3.18. (a) Schematic of a typical MTF and the definition of the SR. Simulated and experimental data of metalenses with inclined sidewall angles. (b) Normalized focal spot intensity. (c) Focal length. (d) Strehl ratio.

3.4.4 Uniform CD bias

In this section, we intentionally applied uniform biases, ΔD , ranging from -30 nm to +30 nm, to the pillars in the layout design (GDS file) to investigate their effects. All other parameters for EBL and etching were consistent with the reference sample. SEM images were captured post-fabrication, as illustrated in Figure 3.19. We focused on two specific pillars — the largest, with a designed diameter of 338 nm, and the smallest, with a designed diameter of 104 nm — just as we did in Section 3.4.1 to analyze their dimensions. All six samples exhibit uniform biases ΔD within the range of -30 nm to

+30 nm.

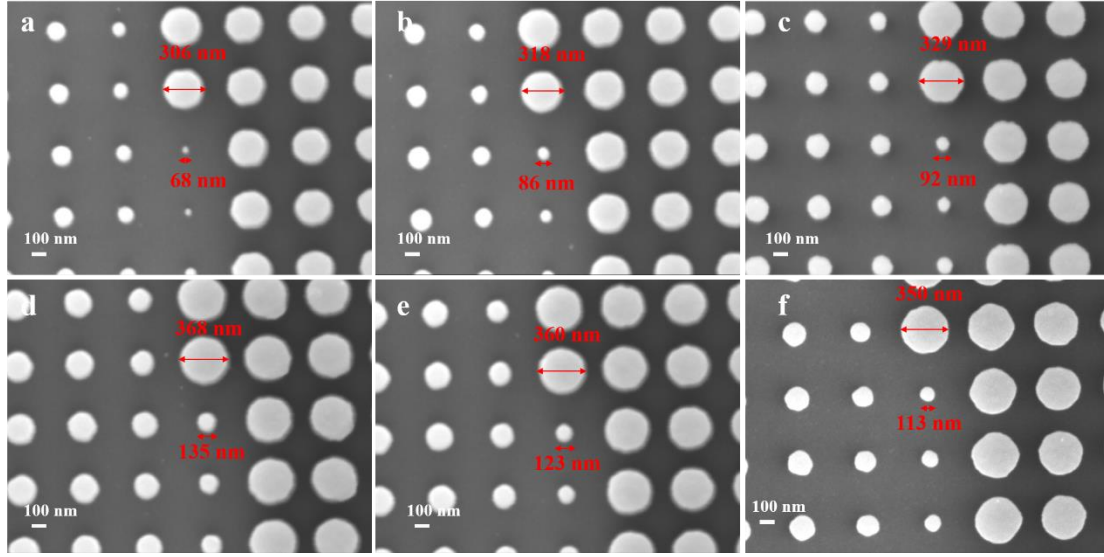


Figure 3.19. Top-view SEM images of metalenses with uniform CD bias. (a) CD bias = -30 nm. (b) CD bias = -20 nm. (c) CD bias = -10 nm. (d) CD bias = +10 nm. (e) CD bias = +20 nm. (f) CD bias = +30 nm.

Figure 3.20 presents the intensity of the focal spot, focal length, and the SR of samples (#7-12) exhibiting uniform CD bias ΔD ranging from -30 to 30 nm, encompassing both simulation and experimental data. As depicted in Figure 3.20a, the intensity of the focal spot gradually decreases as the absolute value of ΔD increases, with the peak intensity falling to approximately 85% when $|\Delta D|$ reaches 30 nm, demonstrating a nearly linear decline. Furthermore, Figure 3.20b highlights that an increase in ΔD leads to a slight increase in focal length, while a decrease in ΔD results in a reduction of focal length. Regarding the SR, as illustrated in Figure 3.20c, it experiences a slight decline with the increase of $|\Delta D|$, indicating a reduction in focusing quality.

This can be attributed to the fact that the diameter of the pillar influences the phase of a nanopillar array with a constant height. As shown in Figure 3.3, the relationship between phase and diameter is non-linear, and the transmission curve does not follow

a straight line. This results in a non-uniform shift of $\Delta\phi D$, leading to an overall alteration in the phase pattern.

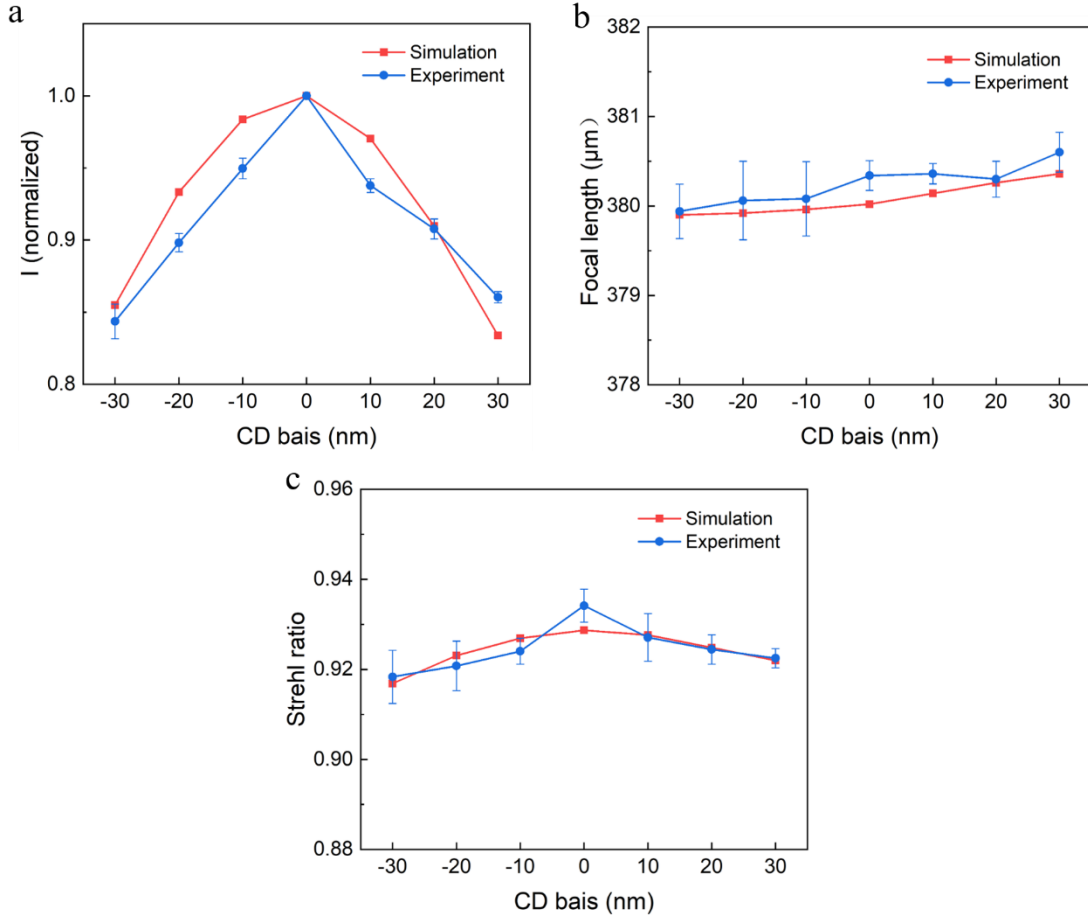


Figure 3.20. Simulated and experimental data of metalenses with uniform CD bias. (a) Normalized focal spot intensity. (b) Focal length. (c) Strehl ratio.

3.4.5 Non-uniform CD bias

As discussed earlier, non-uniform CD bias results from the proximity effect in e-beam lithography. Without PEC, the variation in ΔD will differ for pillars depending on their locations and dimensions. In this section, we fabricated five metalenses (Samples #13-17) without implementing the PEC process before lithography. During the lithography phase, we assigned varying exposure doses to each sample. All five samples were subsequently examined using SEM, and the ΔD for two specific pillars at a fixed

location—the largest ($D = 338$ nm as per design specifications) and the smallest ($D = 104$ nm according to design)—are presented in Table 3.4. In Figure 3.21, we selected two samples with exposure doses of 400 and 450 $\mu\text{C}/\text{cm}^2$ to demonstrate the influence of the proximity effect.

Table 3.4 CD bias of samples without PEC

Sample #	Dose ($\mu\text{C}/\text{cm}^2$)	ΔD-largest pillar (nm)	ΔD-smallest pillar (nm)
1 (With PEC)	300	2	-1
13 (Without PEC)	375	-10	-12
14 (Without PEC)	400	-3	-8
15 (Without PEC)	425	12	-2
16 (Without PEC)	450	20	9
17 (Without PEC)	475	32	16

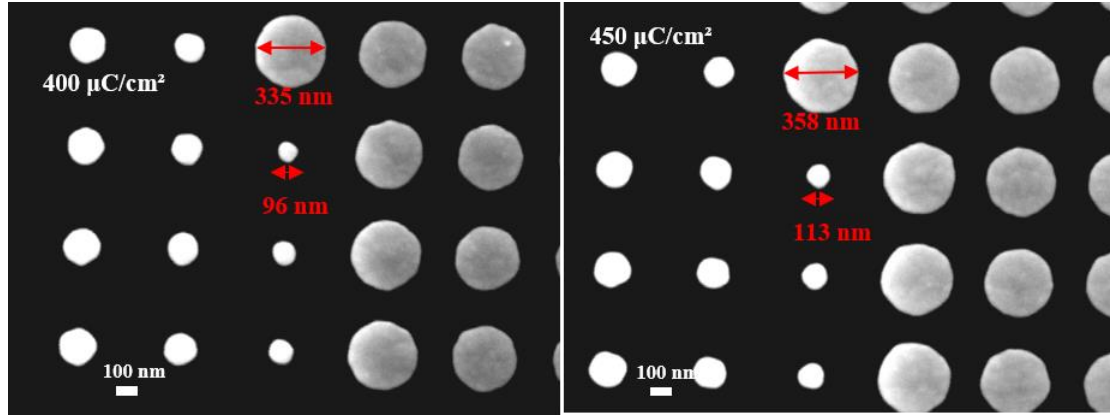


Figure 3.21. Top-view SEM images of metalenses without PEC.

In Figure 3.22, we present experimental data for five samples (#13-17) that were subjected to different exposure doses without PEC, alongside a reference sample (#1) that includes PEC. It is crucial to highlight that comparing the doses between the samples without PEC and the reference sample is not meaningful. This is due to the fact that, when applying PEC, the entire pattern is subdivided into smaller parts, each assigned a different dose factor. The base dose for the reference sample is $300 \mu\text{C}/\text{cm}^2$, but the actual dose for these smaller parts ranges from $150 \mu\text{C}/\text{cm}^2$ (0.5x) to $600 \mu\text{C}/\text{cm}^2$ (2.0x). Thus, only the doses of the five samples without PEC can be compared among themselves.

In Figure 3.22a, the sample with a dose of $400 \mu\text{C}/\text{cm}^2$ exhibited the highest relative focal spot intensity, showing only a 2.5% loss in intensity compared to the reference sample. Other lenses with both higher and lower doses demonstrated inferior intensity results. A similar trend is evident in the focal length and the SR. As shown in Figure 3.22b, the samples with doses of 375 and $400 \mu\text{C}/\text{cm}^2$ yielded focal lengths that were closest to the reference, with a deviation of no more than 200 nm. Regarding the SR, Figure 3.23c indicates that all samples lacking PEC displayed poorer SR and focusing quality; nonetheless, the sample with a dose of $400 \mu\text{C}/\text{cm}^2$ still achieved the best

performance, attaining an SR of 0.927. This represents only a 0.7% reduction compared to the reference sample's SR of 0.934.

Similar to the situation with uniform CD bias, the overall phase pattern is affected by differences in dimensions. It follows that a smaller CD bias leads to better performance. As shown in Table 3.4, the sample of 400 $\mu\text{C}/\text{cm}^2$ produces the lowest overall CD bias, thus allowing this sample to achieve the best performance among the five samples without PEC. In this experiment, we have found that when working with nanostructures of several hundred nanometers and utilizing 100 kV e-beam lithography, the impact of the proximity effect can be minimized through careful exposure dose tuning, resulting in minimal intensity loss, focal length change, and SR drop. This presents a promising opportunity to save both time and cost. In e-beam lithography, the PEC process can be quite time-consuming and requires significant computing power, particularly for larger and more complex designs. Furthermore, the PEC process may increase exposure time, as the entire pattern is subdivided into smaller parts, each requiring a different dose. This results in additional pause time for the e-beam lithography equipment. While the increased pulse time is likely acceptable in research or small batch production, it could pose significant challenges in mass production. Nevertheless, it is feasible to achieve satisfactory results without undergoing the PEC process, making it an appealing option for those aiming to reduce both time and resource investment.

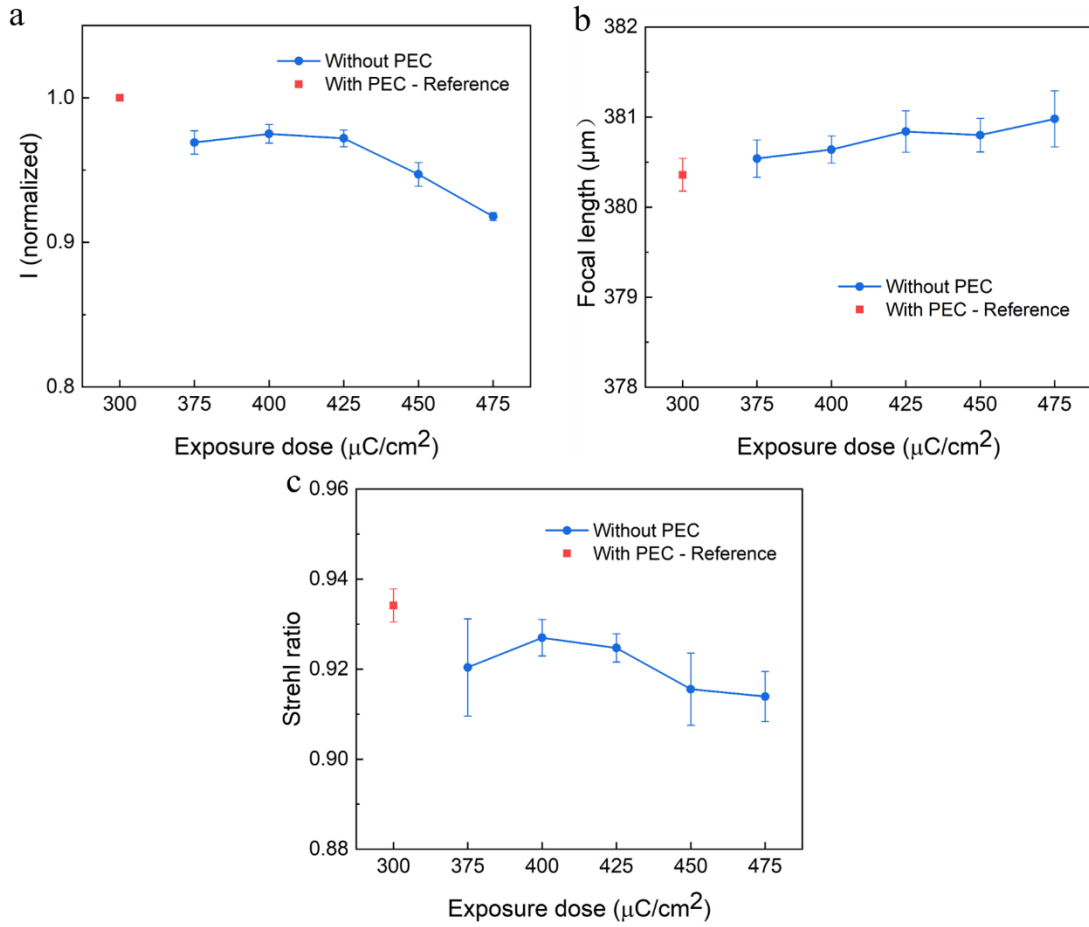


Figure 3.22. Simulated and experimental data of metalenses with non-uniform CD bias. (a) Normalized focal spot intensity. (b) Focal length. (c) Strehl ratio.

3.4.6 Pillar missing

Several studies have addressed the issue of random missing pillars resulting from over-etching¹⁰⁷. However, in practical terms, this defect is not truly "random." During the etching process, smaller pillars are particularly vulnerable and may collapse unless the etching recipe is carefully calibrated to minimize the notching effect. We applied a standard non-switching mixed gas etching recipe in the etcher on sample #18. After fabrication, SEM images were taken to check its etching profile. As shown in Figure 3.23, small pillars ($D < 140$ nm) tend to collapse, whereas all larger pillars remain intact, leading to approximately 4% of the pillars being absent. Additionally, to examine the

effect of varying percentages of missing pillars, we conducted simulations under three different scenarios: missing $D < 120$ nm pillars (1.5%), missing $D < 140$ nm pillars (4%), and missing $D < 160$ nm pillars (7.5%).

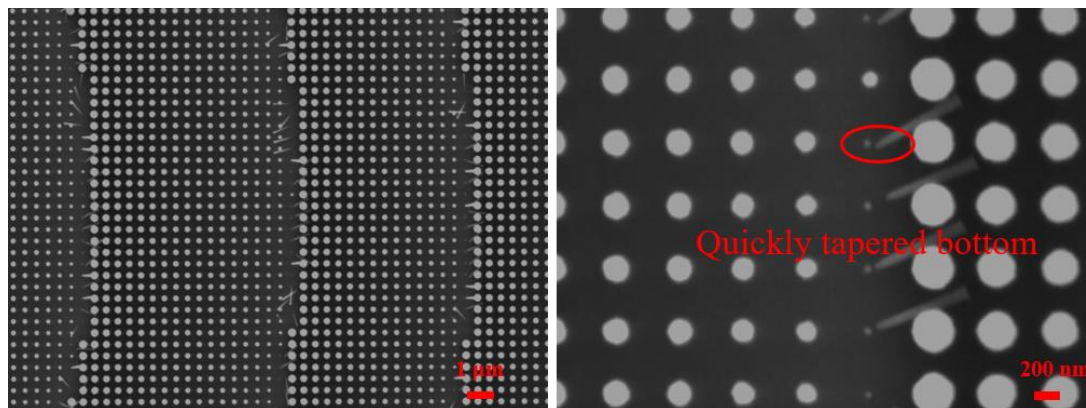


Figure 3.23. Top-view SEM images of nanopillars collapsed due to the notching effect.

Figure 3.24 presents the simulated and experimental results. Notably, a significant difference exists between our experimental findings and the simulation. In the simulation, the focal spot intensity experiences a slight decline, attributed to the low percentage of missing pillars ($< 7.5\%$). Furthermore, both focal length and SR remain unchanged across all four scenarios, which can explain the consistency of the overall phase pattern. The absence of pillars does not introduce phase errors for each individual pillar, differing from cases of CD bias or tapered sidewalls. Additionally, since the missing pillars are not randomly distributed and the metalens are rotationally symmetric, the overall phase pattern retains symmetry even with some pillars absent, ensuring that the focal spot remains unaffected.

In the experimental results, when pillars with a diameter smaller than 140 nm were absent, the intensity of the focal spot rapidly decreased to 87.6%. Additionally, the focal length was reduced by 800 nm, and the SR significantly dropped from 0.934 to 0.915. This happens because the notching effect creates three distinct defects. The first defect

is the absence of pillars. The second defect features an inclined SA at the bottom. When the notching effect occurs, the ion flow is deflected due to charge accumulation, causing it to strike the sidewall. This leads to an increased SA at the base of the pillar and creates a narrower footing (as illustrated in Figure 3.23b). Smaller pillars are more susceptible to collapse from this effect; however, larger pillars, while they may not collapse, still experience negative impacts, including a loss of their vertical sidewalls. The final defect is that collapsed pillars do not vanish during or after fabrication, which blocks the gaps between other pillars and certain substrates. This blockage also introduces phase errors.

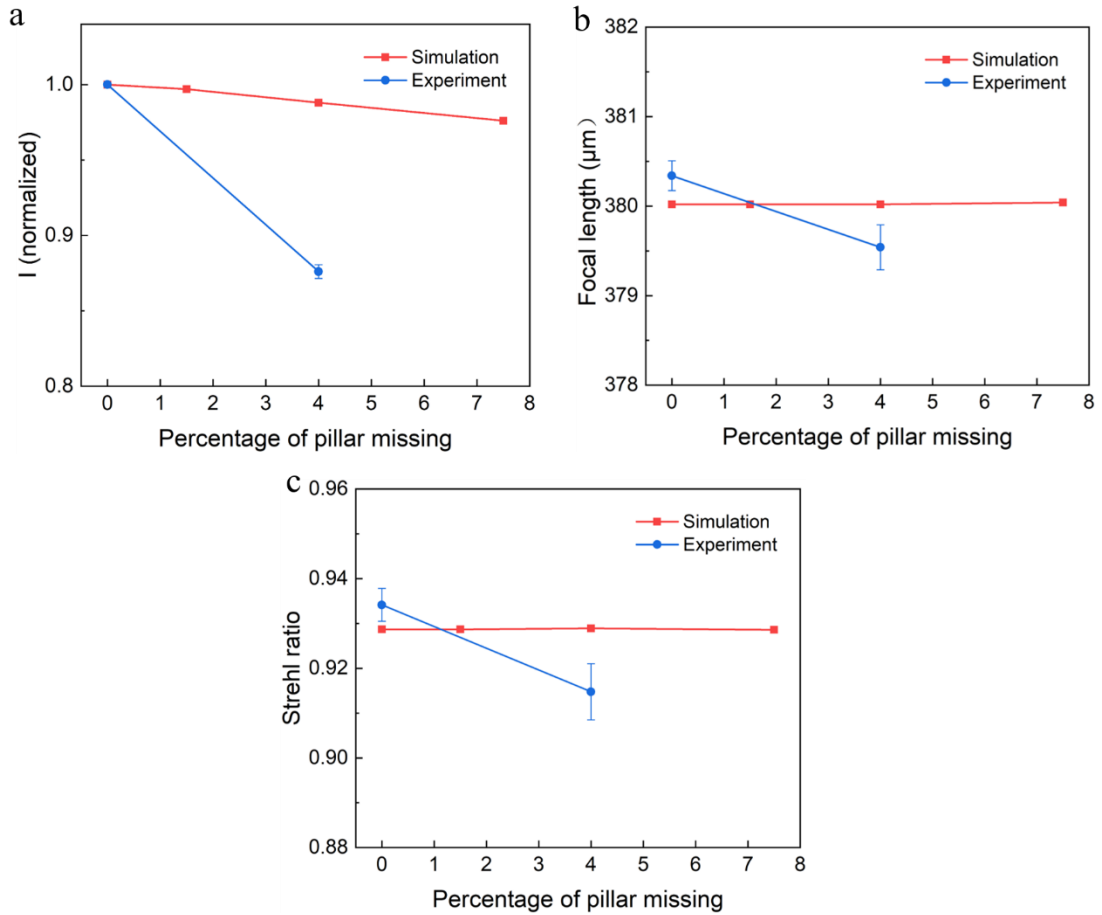


Figure 3.24. Simulated and experimental data of metalenses with the notching effect. 1.5%, 4%, and 7.5% of the missing pillars represent the absence of pillars with D less than 120 nm, 140 nm, and 160 nm, respectively. (a) Normalized focal spot intensity. (b) Focal length. (c) Strehl ratio.

3.5 Conclusion

In summary, our experiment examined the effects of four common defects—inclined SA, uniform CD bias, non-uniform CD bias, and pillar missing—on the optical performance of metalenses. We assessed the impact of these defects by measuring and calculating focal spot intensity, focal length, and SR. Firstly, an SA angle less than 90° resulted in a significant linear reduction in focal spot intensity (11% per degree), a slight decrease in SR, and a marginal increase in focal length. Conversely, an inclined SA angle greater than 90° led to a smaller reduction in focal spot intensity (5% per degree) but caused a notable decline in SR. Secondly, uniform CD bias produced a dramatic, almost linear decrease in focal spot intensity (5% per 10 nm), alongside a slight increase in focal length with a greater ΔD and a small reduction in focal length with a lesser ΔD , as well as a slight decrease in SR. Thirdly, non-uniform CD bias demonstrated minimal loss in intensity and SR, with a slight increase in focal length compared to the reference metalens, suggesting the potential to achieve satisfactory results without employing the PEC process. Finally, the notching effect, characterized by the absence of small pillars, significantly diminished focal spot intensity, focal length, and SR—an outcome attributed to both the lack of pillars and the inclined SA at the pillar bottom. Our research highlights the necessity of understanding and addressing process-induced defects in the production of metalenses.

Chapter 4: A novel multi-step plasma etching of high aspect ratio silicon nanostructures for metalens fabrication

This chapter presents a novel plasma etching technique for creating nanostructures with a smooth sidewall and a controllable taper angle. This technique can be applied in metalens fabrication and can significantly enhance device performance.

4.1 Background and Motivations

Silicon is widely utilized in the fabrication of metalenses for the near-infrared (Near-IR) and infrared (IR) regions, owing to its high effective refractive index and low extinction coefficient. This material comes in various forms, including polycrystalline (p-Si), crystalline (c-Si), and amorphous (a-Si) silicon. In both industrial environments and research laboratories, silicon structures are typically created using dry etching techniques, with Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) becoming a preferred method. Since the optical performance of metalenses heavily relies on the precise etching profile, attaining high-aspect-ratio (HAR) nanostructures is crucial.

However, creating metalens nanostructures through dry etching presents several challenges. Both experimental and simulation studies show that factors such as phase shift, focusing efficiency, and transmissivity are significantly impacted by issues like feature size deviations, sidewall angle variations, and surface imperfections that arise during the etching process. A common deep reactive ion etching (DRIE) technique is the Bosch process, which alternates between passivation and etching steps. However, as mentioned in chapter 2.2.3, the “scroll-like” sidewall profiles produced by this

method can hinder the performance of metalenses.

An alternative DRIE method, silicon cryogenic etching, utilizes SF_6/O_2 plasma at low temperatures to create HAR silicon nanostructures with smooth sidewalls¹¹⁷. Although this approach is effective, it faces challenges related to cryogenic operating temperatures and the impact of crystal orientation^{118,119}. Another promising technique is a continuous ICP-RIE process that employs $\text{C}_4\text{F}_8/\text{SF}_6$ gases at room temperature. In this method, fluorine radicals react with silicon atoms to drive the etching process, while fluorocarbon species from C_4F_8 form a passivation layer on the sidewalls. Directional etching is then achieved as SF_x^+ ions bombard the passivation layer, and free radicals and ions facilitate the deposition of additional fluorocarbon films^{120,121}. The ion distribution angle (IDA), influenced by the bias voltage, plays a crucial role in directing the etching process for HAR nanostructures¹²². Notably, when using a single-step etching process with $\text{C}_4\text{F}_8/\text{SF}_6$ plasma, a change in sidewall angle is observed—likely due to the differing IDAs of C_xF_y and SF_x ions, as well as the depletion of radicals within HAR structures¹²³. This complicates the achievement of the desired HAR nanostructures for metalenses through simple adjustments of gas ratios or bias voltages.

To address these issues, this chapter introduces a continuous, multi-step ICP-RIE process that meticulously adjusts the $\text{C}_4\text{F}_8/\text{SF}_6$ gas flows to optimize both passivation and etching at various depths. By sustaining the plasma between process steps, this method generates smooth sidewalls and nearly vertical profiles, effectively removing the transition point observed during etching. These advancements are anticipated to enhance the fabrication of HAR nanostructures, improving metalens performance and expanding their application potential.

4.2 Experiment and process flow

Figure 4.1 presents the complete procedure for ICP-RIE etching of metalens nanostructures. First (Figure 4.1a), (100) silicon wafers were cleaned using acetone and isopropyl alcohol (IPA). A 220 nm ZEP 520A e-beam resist layer was subsequently spin-coated onto the wafers, followed by a 3-minute bake at 180 °C on a hotplate. The next step (Figure 4.1b) involved conducting electron beam lithography with the JBX-6300FS EBL System at an accelerating voltage of 100 kV and a base dose of 320 $\mu\text{C}/\text{cm}^2$. Afterward, the samples were developed in N50 developer (Zeon Corporation) for 90 seconds and rinsed with IPA. Following this, a 15 nm layer of chromium oxide (Cr_2O_3) was deposited onto the samples using the Intlvac Nanochrome II e-beam evaporator under a vacuum of 4×10^{-6} Torr (Figure 4.1c). The lift-off process involved soaking the sample in N-methyl-2-pyrrolidinone (Remover PG, Kayaku Advance Materials), which transferred the resist pattern into the Cr_2O_3 layer (Figure 4.1d). The ICP-RIE etching of silicon was then executed with the Oxford PlasmaLab 100 ICP 380 DRIE system (Figure 4.1e). Finally, as depicted in Figure 4.1f, the Cr_2O_3 mask was removed using a chromium etchant (Sigma-Aldrich).

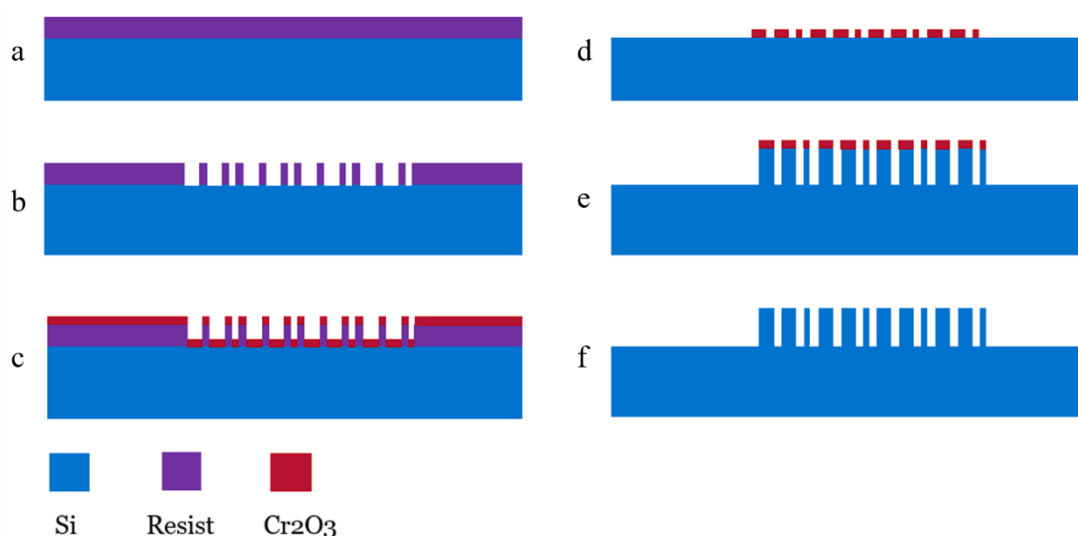


Figure 4.1. Process flow of the fabrication. (a) E-beam resist spin-coating. (b) E-beam lithography and development. (c) Mask evaporation. (d) Lift-off. (e) ICP-RIE etching. (f) Mask removal.

To investigate the effects of the C_4F_8/SF_6 gas ratio on etching profiles and rates, experiments were conducted with a fixed total gas flow of 60 sccm. The flow of C_4F_8 was incrementally increased from 32 sccm to 42 sccm, while the flow of SF_6 was correspondingly decreased from 28 sccm to 18 sccm. Other experimental parameters included a pressure of 10 mTorr, an RF bias power of 50 W, an ICP power of 1200 W, and a maintained temperature of 15 °C. Samples were affixed to 4-inch silicon carrier wafers using Crystalbond™ 555 adhesive to facilitate efficient heat transfer. Notably, a transition in the etched profile was identified at a depth of 500 nm with a C_4F_8/SF_6 ratio of 34:26, followed by another shift at a depth of 1 μm with a ratio of 35:25.

Cr_2O_3 was chosen as the optimal mark for ICP-RIE etching due to its exceptional selectivity to silicon and minimal lateral undercut. When utilizing C_4F_8/SF_6 plasma, the selectivity of silicon to Cr_2O_3 can exceed 100:1, as Cr_2O_3 does not undergo significant reactions with reactive species¹²⁴. A Cr_2O_3 mask results in approximately half the lateral undercut etching of a metallic mask due to the reduction of the metal's catalytic effect¹²⁵. To be precise, the selectivity of silicon to Cr_2O_3 was determined to be 86:1, using an RF bias power of 50 W and C_4F_8/SF_6 gas flows of 38/22.

4.3 Single-step etching of Si

This section describes a single-step etching process in which the etching was continuous and the C_4F_8/SF_6 gas ratio remained constant throughout the procedure.

4.3.1 Effect of C_4F_8/SF_6 gas ratio

During the etching process, silicon atoms react with fluorine radicals, resulting in silicon etching. At the same time, fluorocarbon species from C_4F_8 generate fluorocarbon films that act as a passivation layer on the sidewalls. This passivation layer

is then bombarded by SF_x^+ ions, leading to directional etching. In addition, F-C free radicals and ions assist in the formation of fluorocarbon films. Adjusting the gas ratio is the most effective way to control the taper angle. The taper angle is defined as the angle between the substrate normal and the sidewall of nanopillars, as shown in Figure 4.2. With a higher C_4F_8 ratio, a more positively tapered profile is achieved. Figure 4.3 illustrates the effect of the $\text{C}_4\text{F}_8/\text{SF}_6$ gas ratio on the taper angle and silicon etch rate. The experiment was performed at a consistent pressure of 10 mTorr, with 50 W RF bias power, 1200 W ICP power, and a temperature of 15°C. An increase in the ratio from 1.14 (32 sccm C_4F_8 flow over 28 sccm SF_6 gas flow) to 2.33 (42 sccm C_4F_8 flow over 18 sccm SF_6 gas flow) caused the taper angle of the silicon pillars to change from -2.9° to 5.8° , while the etch rate decreased from 650 nm/min to 310 nm/min. This reduction in etch rate is attributed to enhanced passivation on the bottom and sidewalls, which results in less lateral and vertical etching. Moreover, greater bombardment is required to etch through the passivation layer. Notably, when using a gas ratio of 1.3 (34 sccm C_4F_8 flow over 26 sccm SF_6 gas flow), the top 300 nm of the pillar exhibits a taper angle of 2.1° (marked with an upper empty star), while the bottom 200 nm has a taper angle of -4.1° (marked with a lower empty star). The filled star indicates an equivalent taper angle of -0.78° for the entire nanopillar. The taper angle can be either positive or negative with other gas ratios, with no observed transition.

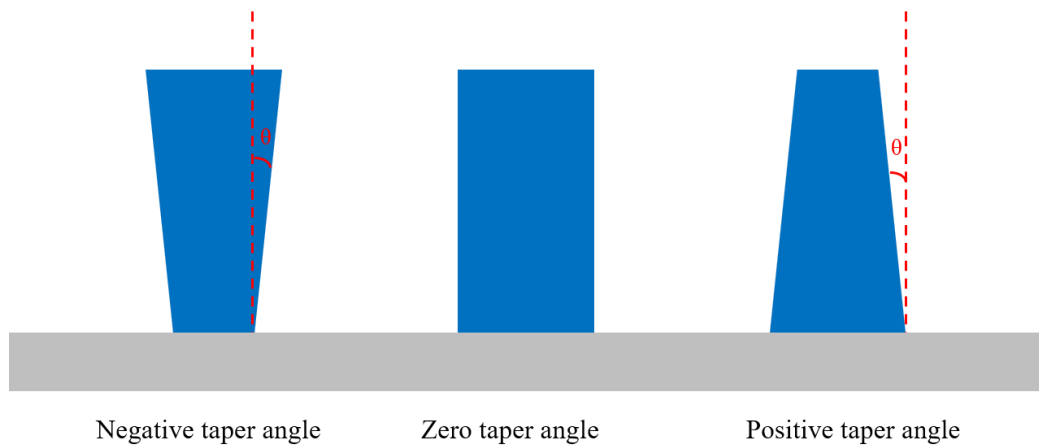


Figure 4.2. Definition of the taper angle.

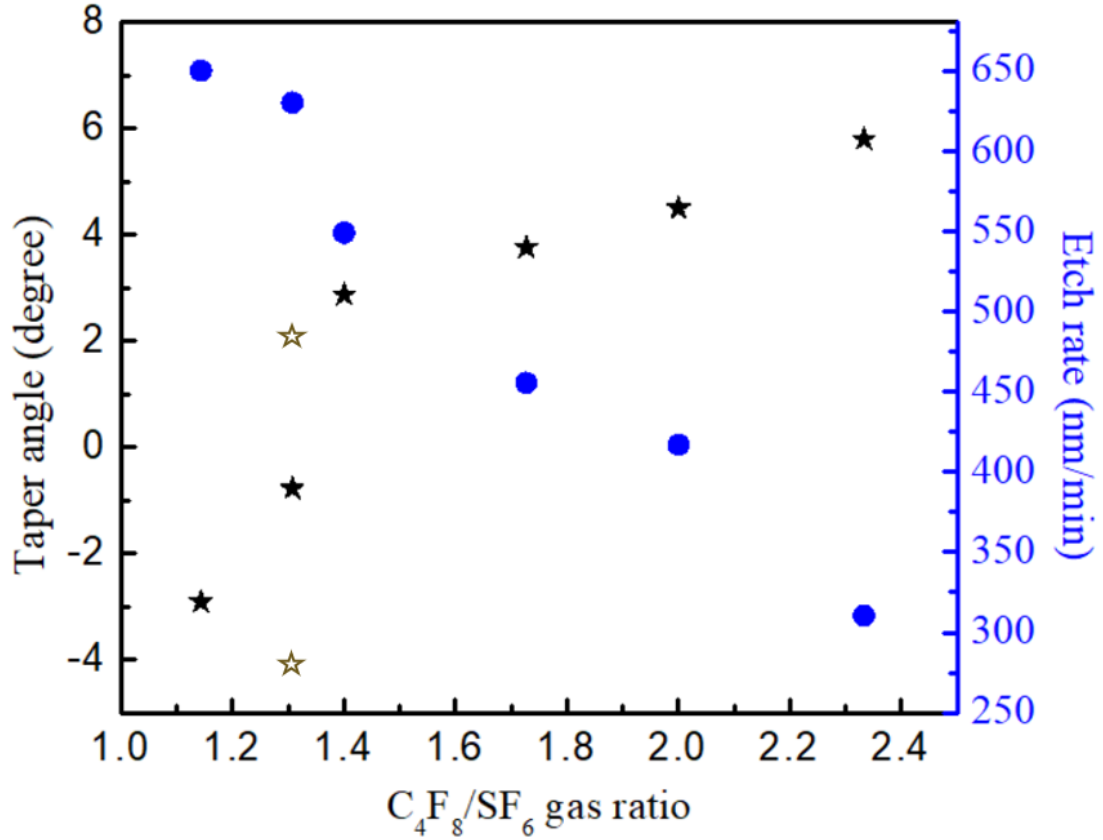


Figure 4.3. The impacts of C_4F_8/SF_6 gas ratio on the taper angle and etch rate.

4.3.2 Profile transition in the single-step etching

According to the results presented in Figure 4.3, the taper angles for gas ratios of 1.14 and 1.4 are -2.91° and 2.87° , respectively. The taper angle was anticipated to be nearly vertical when the gas ratio was 1.3. However, Figure 4.4 reveals a noticeable transition of the taper angle at an etching depth of approximately 300 nm. To investigate this transition, metalens nanostructures with a height of 1 μm were etched under specific conditions, including 35 sccm C_4F_8 gas flow, 25 sccm SF_6 gas flow, 10 mTorr pressure, 50 W RF power, 1200 W ICP power, 15 $^\circ C$, and 110 seconds of etching time. As illustrated in Figure 4.5, the pillars display positive tapering at the top and negative tapering at the bottom, with a transition occurring at a depth of 340 nm, where the taper angle shifts from positive to negative.

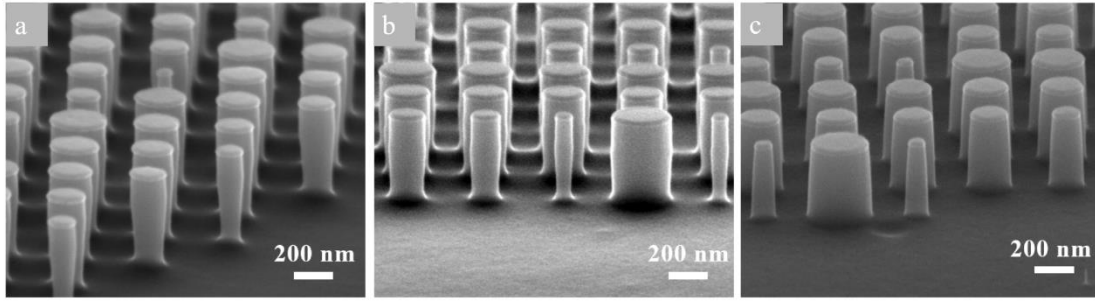


Figure 4.4. SEM images of etched silicon pillars at C_4F_8/SF_6 gas flow ratios of (a) 32/28, (b) 34/26, and (c) 35/25.

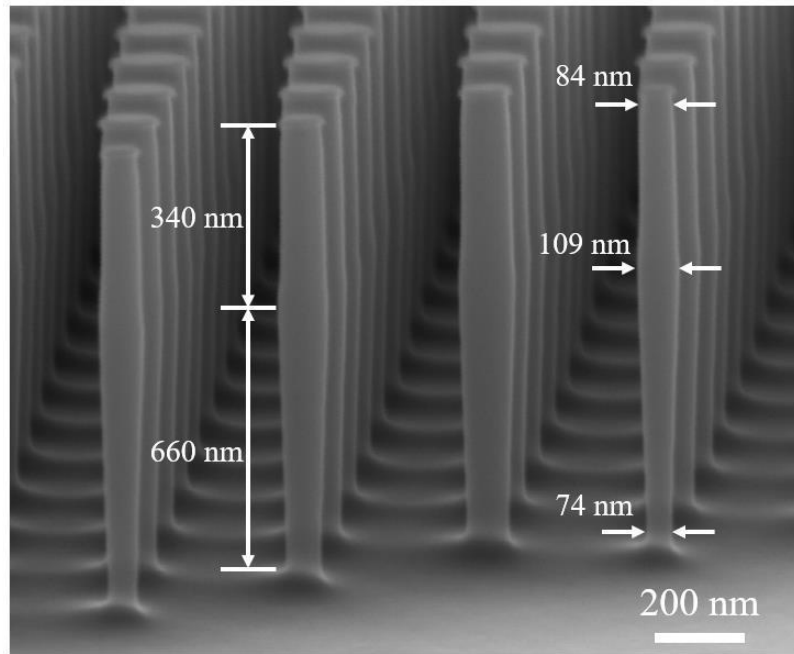


Figure 4.5. Profile transitions at the sidewalls of 1 μm height silicon pillars etched using a 34/26 gas flow ratio.

The performance of single-step ICP-RIE silicon etching depends on several factors, including ion shadowing, neutral shadowing, Knudsen transport of neutrals, and the charging effect. When the sample is subjected to incident electrons and ions, the resultant charging effect can modify the feature profiles. Figure 4.6 illustrates that the transition at the sidewalls is mainly due to ion shadowing and the charging effect, rather than neutral transport. During the etching process, the hard mask and upper sidewall surfaces experience electron accumulation, leading to slight undercutting and lateral

etching. As positive ions strike the feature bottom, the area becomes positively charged, which causes the incoming ions to deflect toward the sidewalls. This results in an increased ion bombardment and the removal of the passivation layer on the lower part of the sidewall.

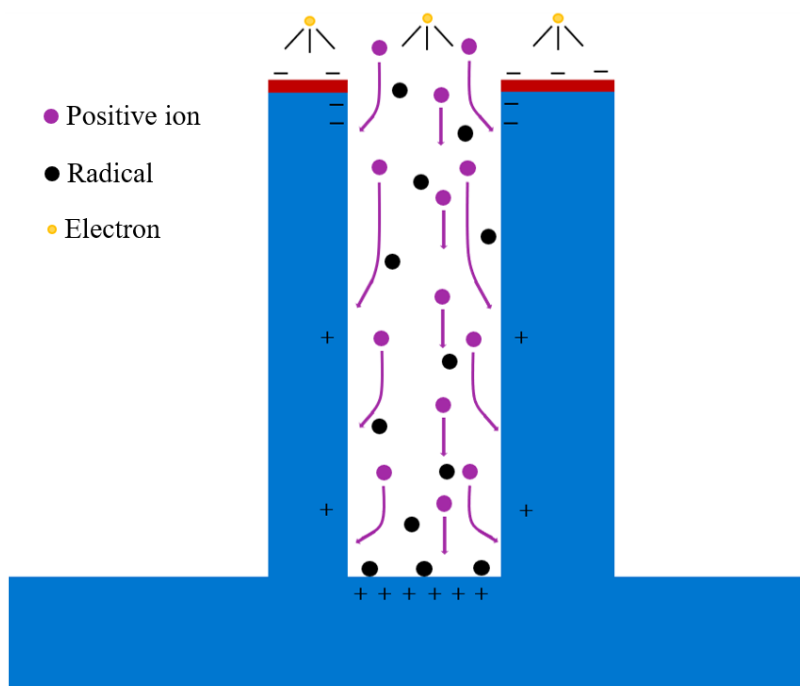


Figure 4.6. Schematic of the positive charging effect during the C_4F_8/SF_6 plasma etching. The positive ions are deflected towards the side walls due to the positive charge at the bottom.

It is widely recognized that the size of the structure impacts how surface charging occurs. For example, when etching 20 nm wide silicon walls with C_4F_8/SF_6 plasma, the resulting profile shows a significant undercut beneath the top portion of the structure, extending for tens of nanometers. In contrast, when etching 8 μm silicon trenches using a single-step C_4F_8/SF_6 plasma process, the profile transitions occur at a depth of approximately 20 μm . Furthermore, the IDAs of CF_3^+ and SF_3^+ ions also contribute to preferentially removing polymer from specific surface locations, leading to changes in taper angle. To address this issue, research was conducted on multi-step etching, incorporating both separate and continuous processes.

4.4 Multi-step etching of Si

This section describes two types of multi-step etching processes: Separate three-step etching (with the RF power turned off after each step) using different gas ratios and continuous three-step etching. The continuous three-step etching method produced vertical and smooth high-aspect-ratio (HAR) nanostructures for metalens fabrication.

Figure 4.7 illustrates the plasma activation and deactivation sequences for the separate and continuous three-step etching processes. In the separate three-step etching, the plasma was turned off, and the chamber was evacuated before beginning the next step. In contrast, during the continuous multi-step etching, the plasma remained active throughout all three stages, with the ratio of C_4F_8 to SF_6 steadily increasing.

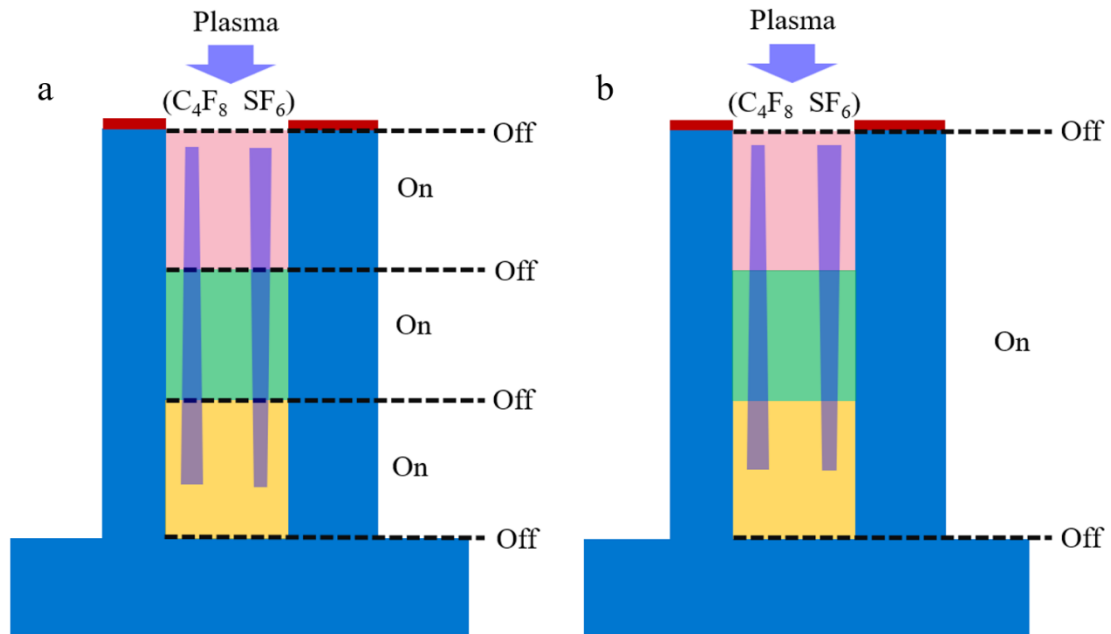


Figure 4.7. Comparison of plasma on-off states between (a) three separate processes and (b) one continuous three-step process.

4.4.1 Separate multi-step etching

To minimize the effects of increased ion bombardment at the lower sections of the

structures, three distinct ICP-RIE etching cycles were performed. In the first cycle, a gas mixture of C_4F_8/SF_6 at 34/26 sccm was utilized for 40 seconds. This was followed by a second cycle with a slightly adjusted ratio of 35/25 sccm for another 40 seconds, and a final cycle employing a ratio of 36/24 sccm for 30 seconds. Throughout all cycles, the process conditions remained constant at a pressure of 10 mTorr, an RF bias power of 50 W, an ICP power of 1200 W, and a temperature of 15 °C. After each cycle, the ICP and RF bias power and gas flows were turned off, and the chamber was evacuated before starting the next etching step. Figure 4.8a illustrates the resulting metalens nanostructures, which reach a height of 1 μm and exhibit three distinct sections corresponding to each etching stage. Notably, an increase in the C_4F_8/SF_6 gas ratio results in a larger pillar diameter, a consequence of enhanced passivation. However, this multi-step process did not yield a better etching profile than single-step etching, and the resulting "scroll-like" sidewalls are likely to significantly negatively impact optical performance.

4.4.2 Continues multi-step etching

A continuous three-step etching process was implemented using the same gas ratios and durations outlined in section 4.4.1, but with the plasma kept continuously active between steps. As shown in Figure 4.8b, this method produced etched pillars with a smooth, negatively tapered profile. The gas ratios and etching times for each step were consistent with those used in the separate etching stages. A negative taper at the base indicates that passivation was insufficient in these deeper regions. This continuous process achieved a more uniform profile by removing the transient phases related to plasma ignition and shutdown.

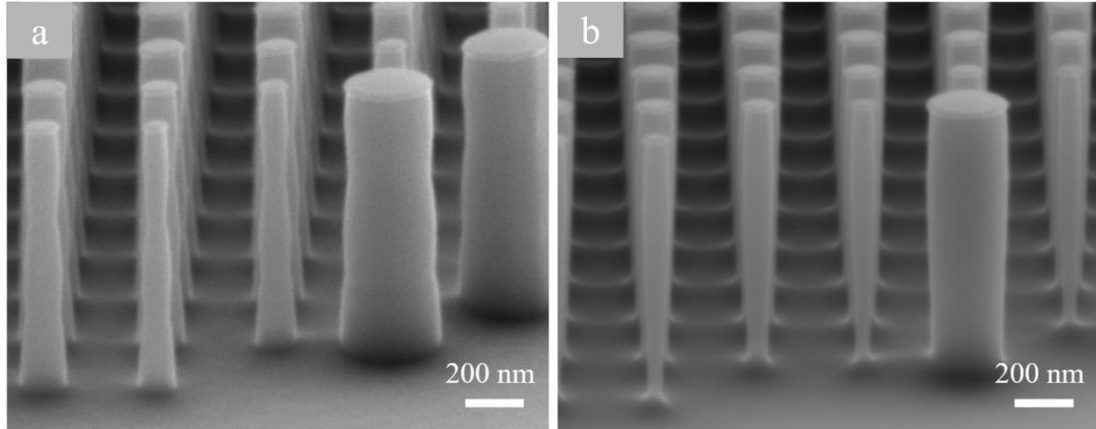


Figure 4.8. Etched metalens nanostructures using (a) three separate recipes and (b) one continuous recipe containing three-step etching.

Unlike a single-step etching approach, the continuous three-step process provides greater flexibility in adjusting gas ratios and fine-tuning the balance between passivation and etching throughout the procedure. To further enhance the verticality of the nanostructures, two specific etching protocols—labeled Process I and Process II in Table 4.1—were developed. In Process I, the first step used C_4F_8 and SF_6 flows of 34 sccm and 27 sccm, respectively. For the subsequent steps, the SF_6 flow was lowered to 25 sccm, and in the final step, the C_4F_8 flow was increased to 35 sccm. SEM images (Figure 4.9a) of these structures showed a well-passivated, vertical upper section. At the same time, the lower part remained negatively tapered, indicating that the passivation during the second and third steps was insufficient.

To address this, Process II adjusted the gas flows by increasing the C_4F_8 rate while reducing the SF_6 flow during the second and third steps. As illustrated in Figure 4.9b, this modification led to smooth, nearly vertical profiles for the metalens nanostructures. These findings indicate that a multi-stage approach to modifying etching parameters offers improved control over both passivation and etching, ultimately resulting in the desired vertical profile in the nanostructures.

Table 4.1 Parameters for the continuous three-step etching processes

	<i>Process I</i>			<i>Process II</i>		
Step	1	2	3	1	2	3
C₄F₈ (sccm)	34	34	35	34	36	37
SF₆ (sccm)	27	25	25	27	24	23
Pressure (mTorr)	10	10	10	10	10	10
RF power (W)	50	50	50	50	50	50
ICP power (W)	1200	1200	1200	1200	1200	1200
Duration (sec)	40	40	30	40	40	30
Temperature (°C)	15	15	15	15	15	15

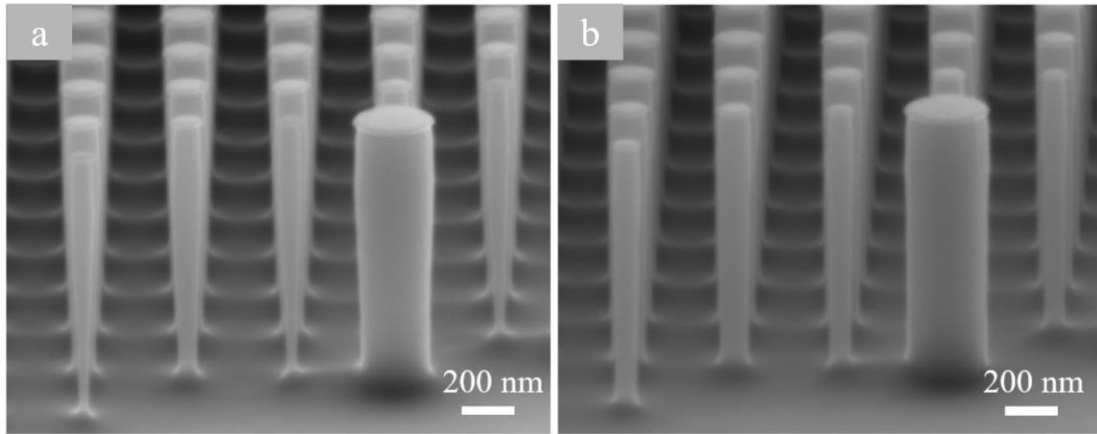


Figure 4.9. SEM images of etched metalens nanostructures showing (a) a negative taper angle and (b) vertical profiles, utilizing Process I and Process II, respectively.

By employing Process II (detailed in Table 4.1), we successfully etched metalens nanostructures arranged in both circular and rectangular arrays, as shown in Figure 4.10. The rectangular elements measure approximately 100 nm in width and 1 μ m in height, while the smallest pillars have a diameter of 71 nm, resulting in an aspect ratio of up to 14. Furthermore, the pillar diameters remain consistent, with less than a 10 nm variation over the full 1 μ m height, demonstrating the exceptional precision of the continuous,

multi-step etching process.

It is crucial to recognize that feature size can influence surface charging, which affects both passivation and etching during the process. As a result, the duration of each etching step must be tailored to the specific feature size, and the gas compositions may need adjustment for each step. These modifications take into account factors such as neutral particle transport and depletion, IDA, aspect ratio-dependent etching, and substrate type—especially when variations in both feature size and height are present.

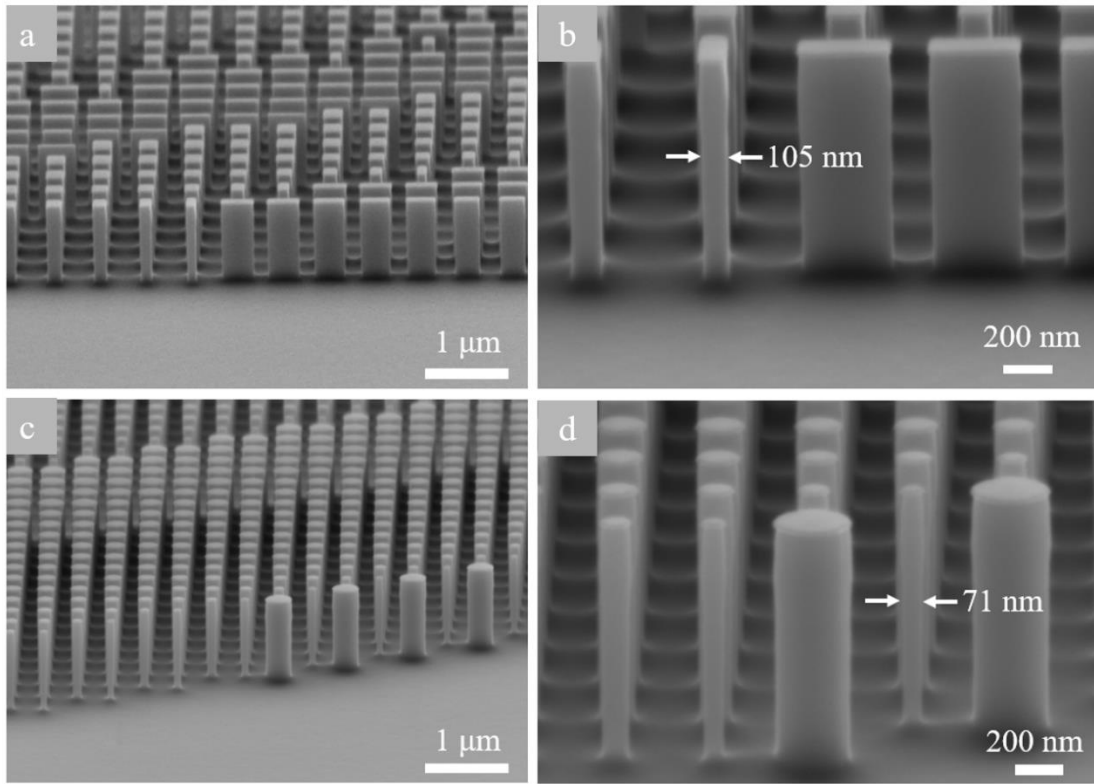


Figure 4.10. Nanostructures of etched metalenses featuring (a) rectangular and (c) circular arrays, along with zoomed-in images represented by (b) and (d).

4.4.3 Notching effect of a-Si pillars

As noted in section 4.3.2, when plasma is used to etch structures, the ion flow can be redirected toward the sidewalls due to charge accumulation on the bottom surface. This

can result in greater lateral etching at the lower portion of the structure. Furthermore, when we choose a-Si on silica substrate as the metalens material instead of on crystalline Si, the notching effect may happen, particularly when an insulating SiO₂ substrate is exposed during etching. Small pillars may even collapse due to the notching effect, as shown in Figure 4.11. Despite following recipe II from Table 4.1, many small structures still collapsed during etching to create rectangular arrays, showing a noticeable decrease in bottom size. To prevent this notching effect, it is important to use more passivation in the final step when etching a-Si on a silica substrate. To obtain improved results without structural collapse, we modified the final stage by increasing the gas ratio from 37/23 to 39/21. The consequent outcome is represented in Figure 4.12.

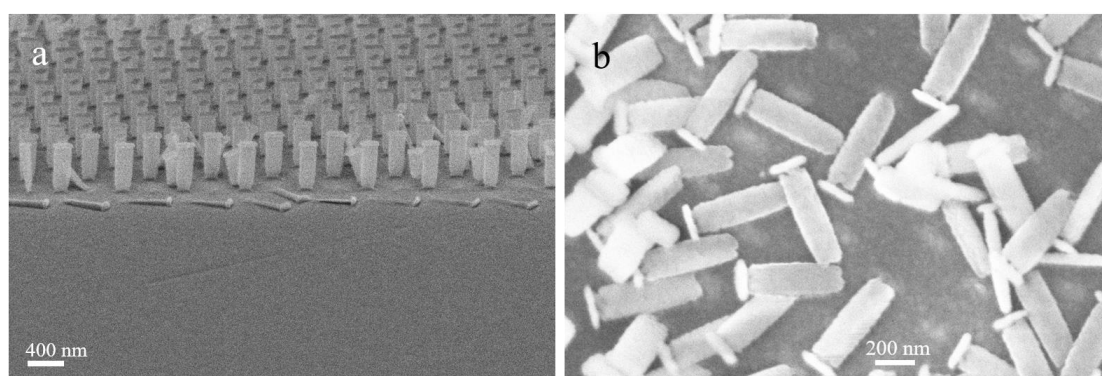


Figure 4.11. Etched a-Si nanostructures with a notching effect.

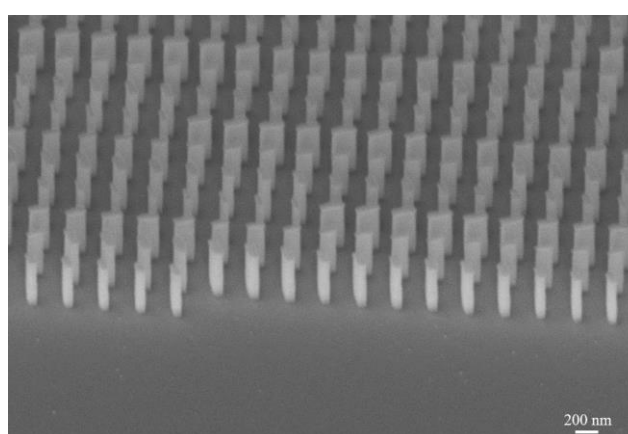


Figure 4.12. Etched a-Si nanostructures with more passivation in the final stage.

4.5 Conclusion

A multi-step ICP-RIE etching technique was developed and evaluated to improve the sidewall quality of metalenses with high-aspect-ratio (HAR) nanostructures. Cr_2O_3 hard masks were chosen for this process due to their excellent selectivity in fluorine plasma etching, with minimized undercutting. The study examined how variations in the $\text{C}_4\text{F}_8/\text{SF}_6$ gas ratio affect the etching rate and the taper angle. Significant changes in the etched profile were noted beyond a certain depth, likely due to charging effects on the sample surface. A comparative analysis between single-step and multi-step etching using $\text{C}_4\text{F}_8/\text{SF}_6$ plasma showed that the multi-step method allows for better control over passivation and etching. This approach provides enhanced flexibility for achieving smooth, vertical HAR profiles. By implementing a continuous three-step etching process, both rectangular and circular HAR nanostructures for metalenses were successfully fabricated. The process enabled the creation of features as small as 70 nm with aspect ratios up to 14. This method's excellent controllability and adaptability make it highly suitable for fabricating metalenses and other devices requiring precise HAR nanostructures.

Chapter 5: Near-infrared single-layer metalens with a large field-of-view

This chapter presents a fabricated single-layer metalens featuring an exceptionally large field of view (FOV). This metalens exhibited a FOV of 120° at a working wavelength of 940 nm, and the experiments revealed effective focusing performance with high efficiency ranging from 35% to 61%, depending on the varying incident angles.

5.1 Background and Motivations

The field of view (FOV) is a crucial metric for assessing the performance of an optical system. Imaging devices with a large FOV can capture light signals from the surrounding environment in a single exposure, thus obtaining more comprehensive information without needing image stitching or mechanical scanning. Traditional lenses with hyperbolic phase profiles typically permit a FOV of less than 10° without introducing aberrations¹²⁶. As the angle of incident light increases, third-order (Seidel) aberrations, including coma, astigmatism, and field curvature, become increasingly significant. To address these aberrations, traditional methods typically involve stacking multiple refractive lenses to form a compound lens system. However, this multi-lens arrangement results in increased size, weight, cost, and complexity of the optical system. In contrast, utilizing generalized Snell's law, metalenses can adeptly manipulate the fundamental properties of incident light waves, such as amplitude, polarization, and phase, opening up possibilities for achieving large FOV with diffraction-limited focusing in a compact and cost-effective design.

Due to its distinctive properties, the near-infrared (IR) region is extensively utilized

across various applications¹²⁷⁻¹²⁹. This wavelength is invisible to the human eye, making it particularly suitable for covert imaging and sensing systems. Additionally, near-IR light strikes an effective balance between penetration depth and resolution, which is advantageous for applications such as facial recognition, night vision, and laser radar. Several designs of metalenses have been successfully implemented to achieve large FOV and diffraction-limited focusing in the near-IR range. Arbabi et al. achieved a 60° FOV at 850 nm using a two-layer cascaded metasurface¹³⁰. In their approach, the first metalens corrects for off-axis aberrations, while the second provides phase compensation for focusing, ultimately facilitating large FOV imaging. In comparison to multilayer metalens structures, single-layer large FOV metalenses present a simpler and more manufacturable solution. For instance, Engelberg et al. showcased outdoor imaging with a single-layer metalens boasting a 30° FOV at 825 nm⁷⁵. Similarly, Xie et al. successfully integrated a metalens with a post-wavevector filter, extending the FOV beyond 120° at a working wavelength of 830 nm¹³¹; however, their device demonstrated low efficiency (approximately 19%) without the wavevector filter. Presently, metalenses operating in the near-IR continue to encounter challenges, including limited FOV, high manufacturing costs, and complex structural designs.

Building on the advancements discussed in the last two chapters, this chapter presents the design and fabrication of a single-layer metalens with a 120° large FOV at a near-IR wavelength of 940 nm. The metalens features a straightforward structure comprised of a metallic aperture and a single-layer metasurface. The metallic aperture is directly integrated on the rear side of the substrate to minimize aberrations. A ray-tracing algorithm was employed to optimize the phase profile of the metalens. The resultant metalens was fabricated and subjected to experimental characterization, including an analysis of focal spot quality at various incident angles to assess its focusing performance. Utilizing our best process control, we achieved high focusing efficiency

(35% to 61%) and diffraction-limited imaging ($SR > 0.8$).

5.2 Design and Simulations

5.2.1 Parameters of the metalens

In Figure 5.1, we illustrate the fundamental components of our metalens design. Our approach utilizes a-Si nanopillars situated on a SiO_2 glass substrate, with structures present on both sides of the glass wafer. On the front side, we have arranged the a-Si nanopillars to form a circular area with a diameter of $940\text{ }\mu\text{m}$. Conversely, the backside of the wafer features a $200\text{ }\mu\text{m}$ hole, which directs light at varying incident angles to different regions of the lens. Each lens section is designed to focus light entering at specific angles. It is crucial to highlight that only the light passing through the hole can be effectively focused and collected, while light directed at other areas will be obstructed.

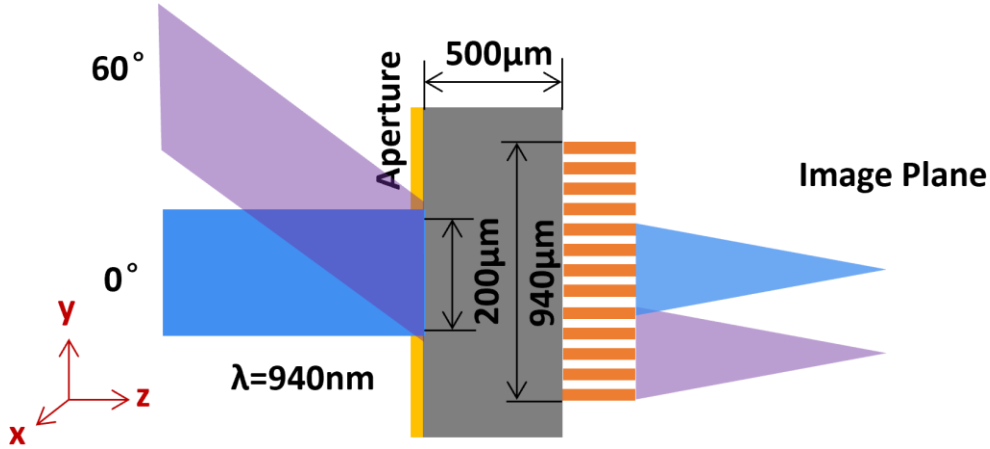


Figure 5.1. Schematic of the large FOV metalens.

The propagation phase was employed to manipulate the wavefront, leading to the selection of polarization-independent pillars as the meta-atoms. Each unit cell measures 400 nm on each side, with the diameters of the pillars varying from 100 to 300 nm . Table 5.1 provides a comprehensive list of all parameters for this metalens.

Table 5.1 Parameters of the unit cell simulation

Pillar height	690 nm
Pillar diameter	100 – 300 nm
Pillar pitch	400 nm
Wavelength	940 nm
Focal length	380 μm
Whole lens diameter	940 μm
NA	0.25

5.2.2 Phase profile design

Conventional focusing metalenses adopt a hyperbolic phase distribution, which results in significant off-axis aberrations. Metalenses with a quadratic phase distribution can achieve a wide field of view. When light hits the metasurface that is positioned in the x-y plane at an incident angle θ to the lens' normal axis, the expected phase profile for focusing the incoming light is expressed as Equation (13):

$$\phi(x, y) = \frac{\pi}{\lambda f} (x^2 + (y + f \sin \theta)^2) - \frac{\pi}{\lambda} f \sin^2 \theta \quad (13)$$

Where k_0 is the free-space wave vector, f is the focal length, and x and y represent the radial positions on the metalens. By ignoring the last constant term in the equation, it becomes clear that oblique incidence leads to a spatial shift of the focal point on the focal plane, as shown in Figure 5.2. As a result, the quadratic phase can convert the phase caused by oblique incidence into spatial displacement, thus allowing for a broader field of view.

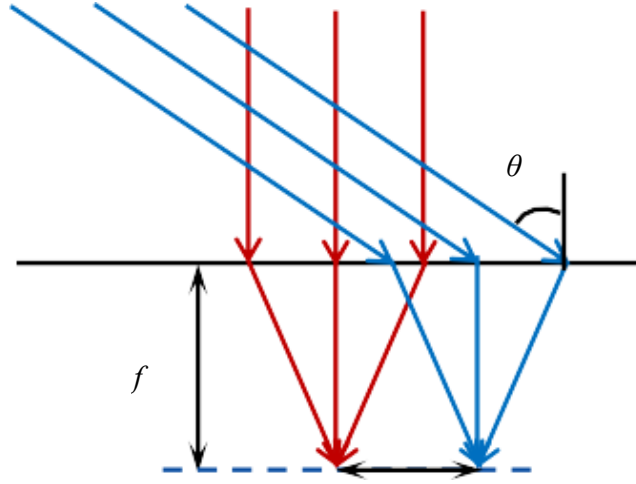


Figure 5.2. Schematic of the quadratic phase distribution.

Here, another commercial simulation tool, Optic-Studio (Zemax), was used to calculate the desired phase wisely. In this tool, the phase profiles have been determined as even-order polynomials of the radial coordinate (ρ), as explicitly stated in Equation (14):

$$\phi(x, y) = M \sum_{i=1}^n a_n \left(\frac{\rho}{R} \right)^{2i} \quad (14)$$

where M is the diffraction order, R is the normalized radius of the metalens, ρ is the radius along the plane of the metalens, and a_n is the coefficients optimized by the tool to achieve the smallest focal spot.

In Zemax, we configure seven distinct incident angles: 0° , 10° , 20° , 30° , 40° , 50° , and 60° (as illustrated in Figure 5.3). Given that the phase profile is rotationally symmetric, the design only needs to encompass a half-field of view from 0° to 60° . The damped least squares method is employed to iteratively optimize the coefficients a_n at a wavelength of 940 nm, aiming to minimize the focal spot size for incident angles ranging from 0° to 60° . The optimized ideal phase profile of the metalens is presented in Figure 5.4. Additionally, the image simulation function in Zemax was utilized to assess the imaging performance of the optimized metalens system, specifically for the original image depicted in Figure 5.5. The results of the simulation reveal that the image

retains notable clarity throughout the entire field of view, reflecting high imaging quality. While barrel distortion—a common challenge in wide-angle imaging systems—was observed, it does not compromise image resolution and can be effectively corrected with image processing software. This confirms that the optimized ideal phase profile of the metalens facilitates clear imaging within a $\pm 60^\circ$ field of view.

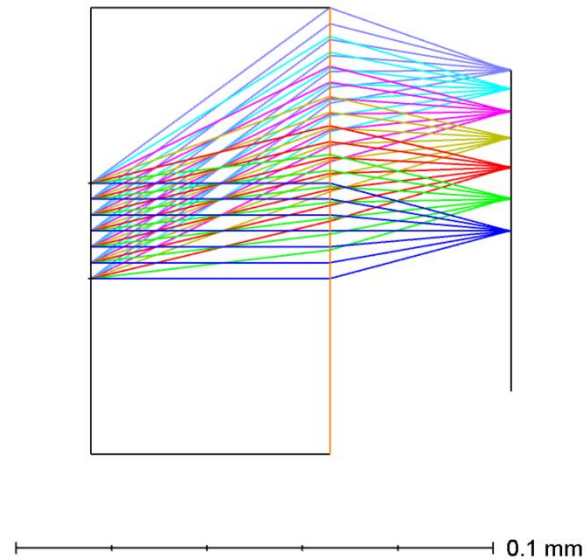


Figure 5.3. Layout of the metalens in Zemax.

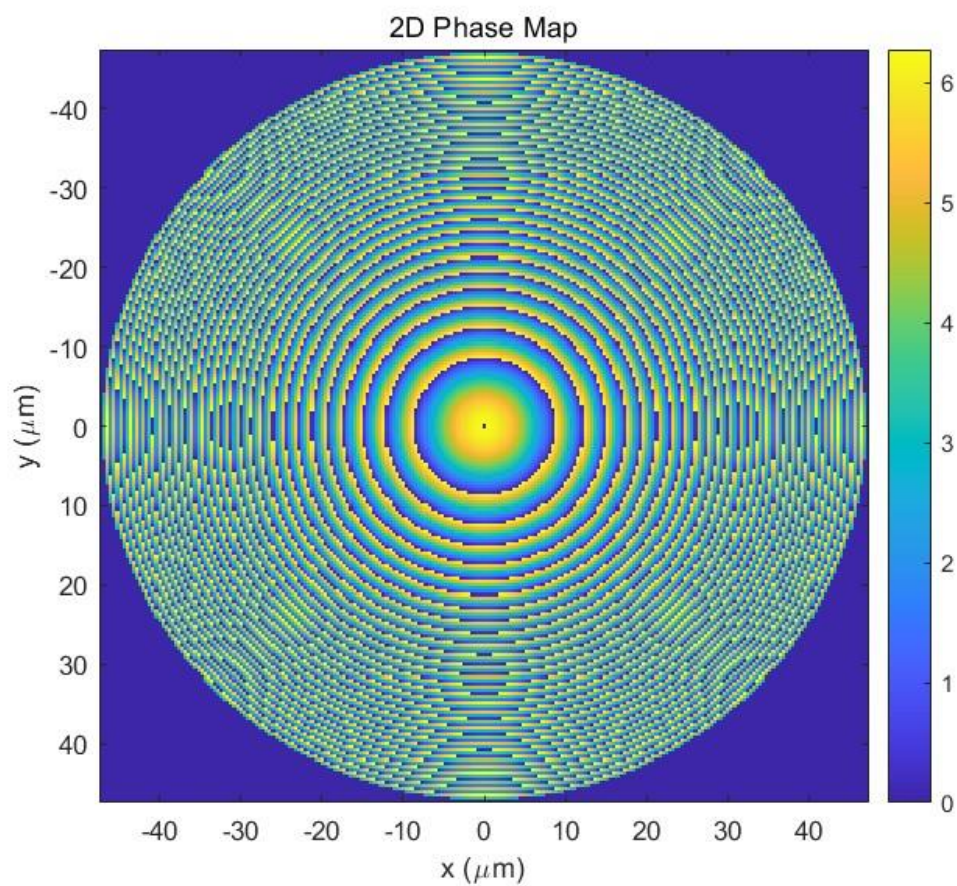


Figure 5.4. Phase map of the full lens.

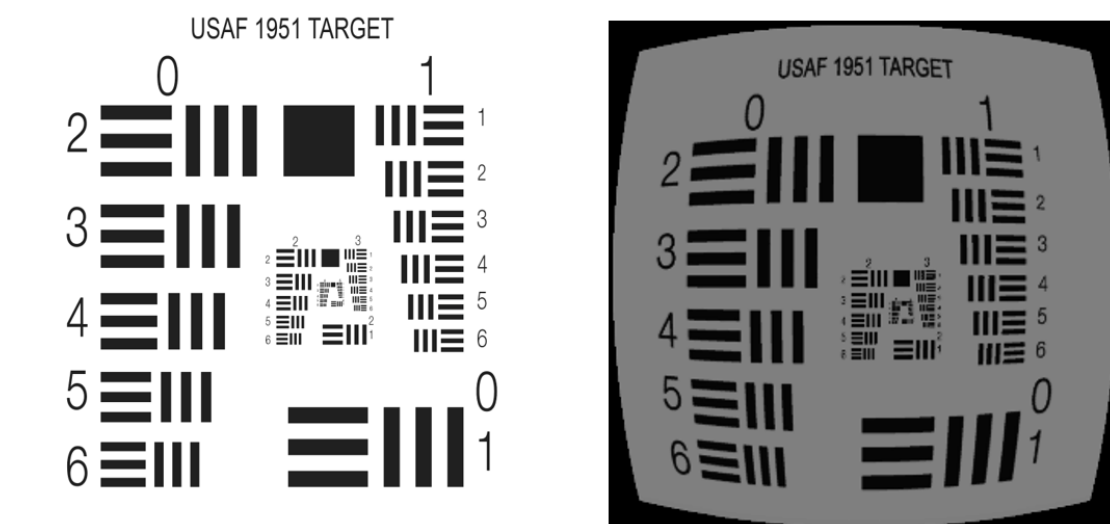


Figure 5.5. Imaging performance simulation for our metalens. Left: the original image; right: the simulated result.

5.2.3 Unit cell design

The designed metasurface structure consists of a-Si nanopillars on a fused silica substrate. According to ellipsometry measurements, the refractive indices of the a-Si and SiO₂ materials at a wavelength of 940 nm are 3.0 and 1.4, respectively. Electromagnetic simulations of the metalens were performed using the finite-difference time-domain (FDTD) simulation software, Ansys Lumerical. The a-Si nanopillars have a height (H) of 690 nm and diameters (D) ranging from 100 nm to 300 nm. They are arranged in a square lattice with a periodicity (P) of 400 nm. The simulated phase and transmission characteristics of the nanopillars as a function of diameter are illustrated in Figure 5.6. The results demonstrate that the nanopillars achieve a phase coverage spanning from 0 to 2π . Notably, the diameter of 300 nm exhibits a transmission anomaly due to resonance, while all other nanopillar sizes maintain remarkably high transmittance. The average simulated transmittance across all nanopillars is 87%. The inset in Figure 5.6 provides a schematic representation of the metasurface unit cell structure.

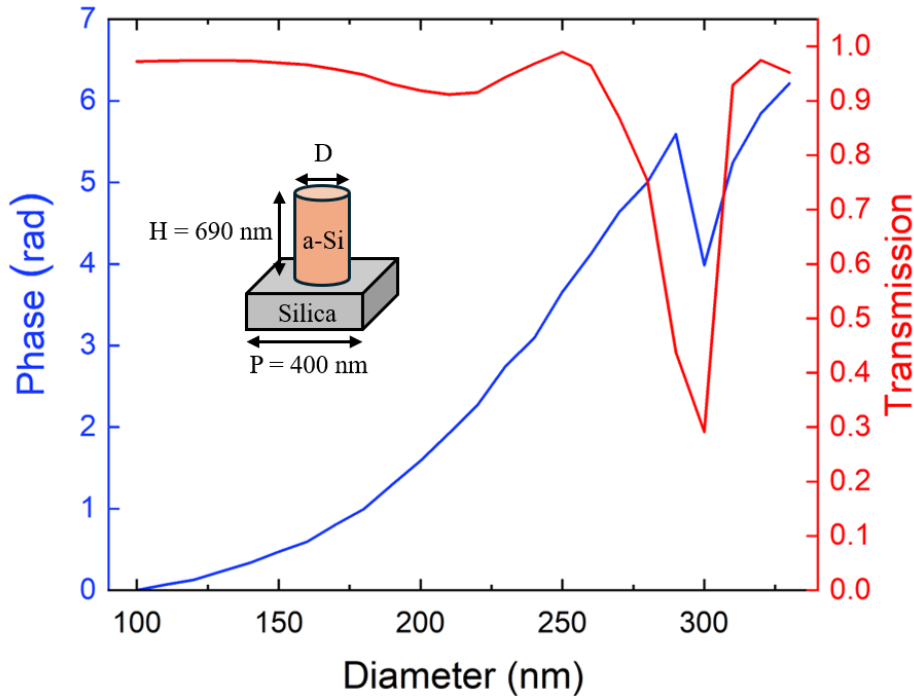


Figure 5.6. Phase shift and transmission related to the pillar diameters.

Following this, we performed a unit cell simulation with an oblique incident angle. Figures 5.7a and b illustrate the simulated results for the phase and transmission of the nanostructures as a function of diameter, considering plane wave incident angles ranging from 0° to 60° . The incident light source is situated within the SiO_2 substrate. It is evident that for incidence angles between 0° and 30° , the phase of the nanostructures is minimally influenced by the angle of incidence, with the average transmittance remaining above 85%. However, for incidence angles between 40° and 60° , the phase curve shows a slight shift, accompanied by a decrease in transmission. At an angle of 60° , the average transmission hits its lowest point, yet still stays above 60%. Overall, the designed metasurface unit structure demonstrates a relative insensitivity to the incident angle.

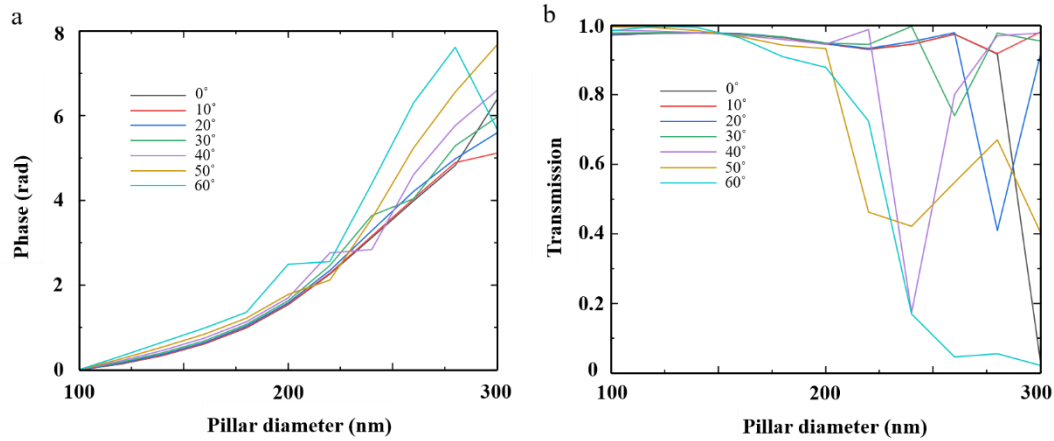


Figure 5.7. Phase shift (a) and transmission (b) related to the pillar diameters at different incident angles.

5.2.4 Full lens simulation

The direct simulation of a large lens poses a considerable challenge. To effectively conduct such a simulation, it is essential to reduce both the lens size and other associated parameters. Accordingly, we have developed a simulation featuring a lens with a diameter of $94\ \mu\text{m}$ (1/10 of the original) and a focal length of $38\ \mu\text{m}$ (1/10 of the original) for analysis.

To evaluate our design, we converted the phase map into nanopillars and constructed the complete lens. A plane wave source, capable of adjusting the incident angle from 0° to 60° and repositioning the beam center, was employed to test the lens's focusing performance under various conditions. Figure 5.8 illustrates the normalized electric field intensity distribution in the focal plane of the metalens for incident angles ranging from 0° to 60° . It is evident that the metalens effectively focuses the incoming light across the entire range, maintaining a well-defined focal spot. On the x-y plane (Figure 5.8a), the focal spot profiles remained round and well-focused from 0° to 50° , although some distortion is noticeable at 60° . All seven incident angles on the x-z plane (Figure 5.8b) yielded a focal length of approximately $38\text{ }\mu\text{m}$, demonstrating reasonable focusing profiles. Next, the focusing efficiency and the overall transmission at different incident angles were simulated. The focusing efficiency is defined as the ratio of the focal spot intensity to the incident light intensity on the metalens. As shown in Figure 5.9, the average simulated focusing efficiency across all incidence angles is 58%, with the lowest efficiency of 44% occurring at a 60° incidence angle. The focusing efficiency curve follows the same trend as the transmittance curve, suggesting that the variation in focusing efficiency at different field angles is related to the loss of transmitted power.

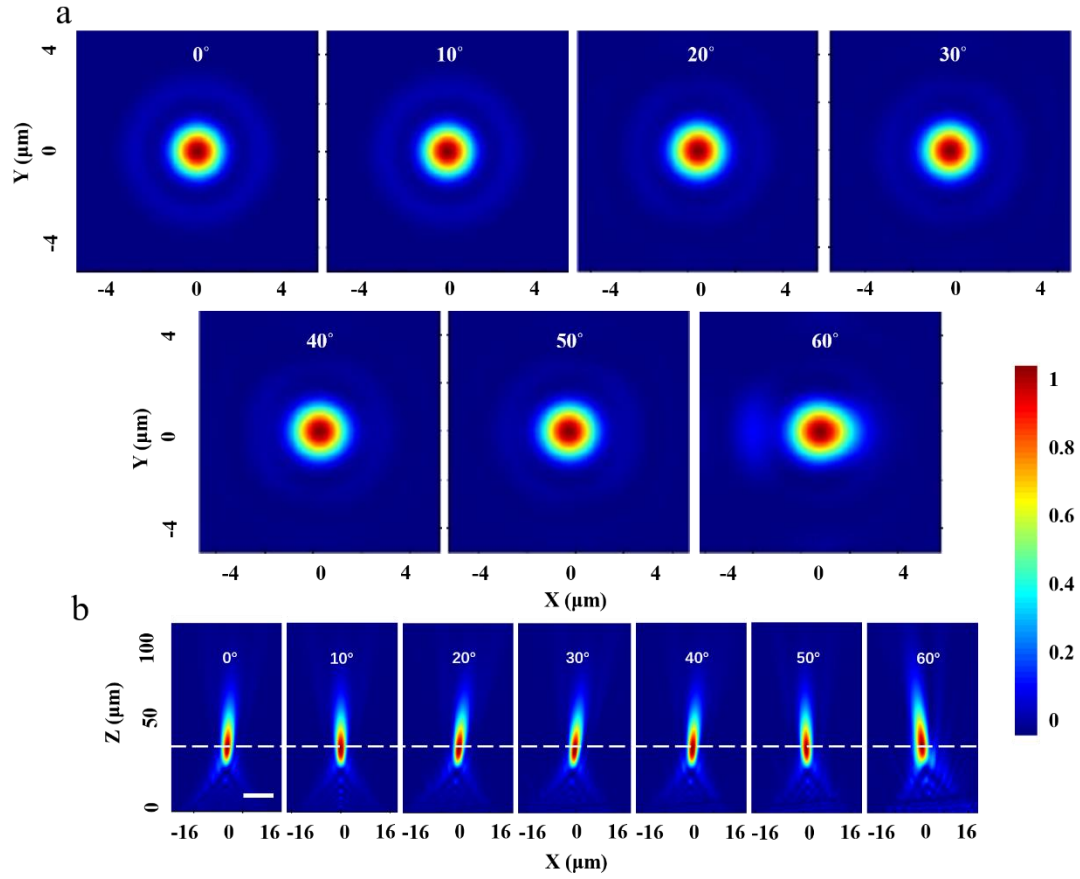


Figure 5.8. Simulated focusing intensity profiles with seven incident angles on x-y (a) and x-z (b) planes.

White dashed lines indicate the focal plane.

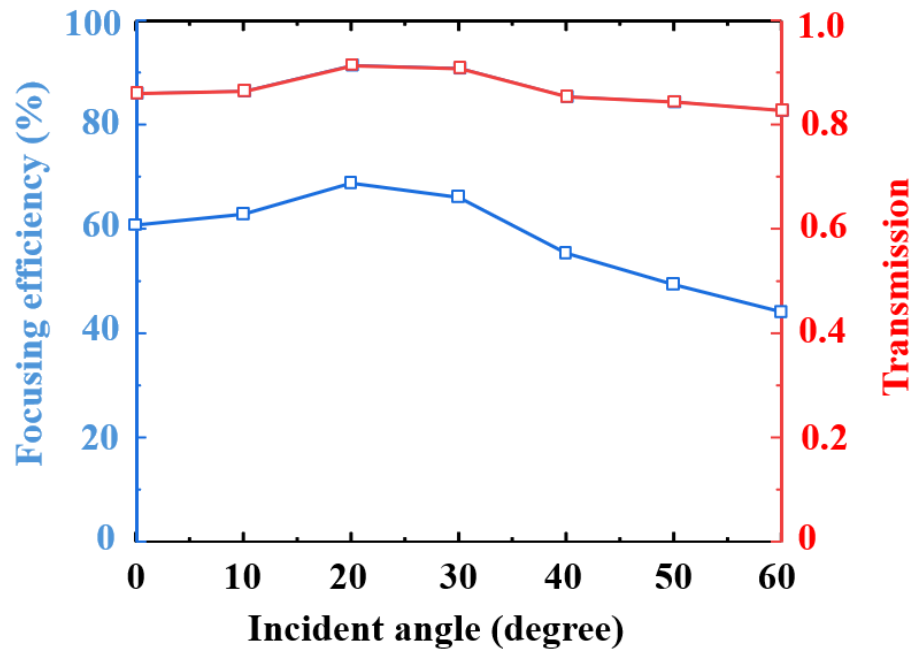


Figure 5.9. Simulated focusing efficiency and transmission at different incident angles.

5.3 Experiments

5.3.1 Process flow

Figure 5.10 shows the whole process of fabrication. Firstly, a fused silica wafer undergoes a thorough cleaning process with acetone and IPA, followed by oxygen plasma cleaning (RF: 20 W; O₂: 20 sccm, 20 mTorr, 2 minutes). Next, a 130 nm Cr layer is deposited by sputtering onto the backside. A photoresist S1811 is then spin-coated onto the Cr and then exposed by a direct write UV lithography system (Heidelberg MLA). After development using MIF319 developer, Cr is etched by soaking the sample into the Cr etchant. Then, the photoresist is removed by PG remover. Next, 690 nm a-Si is deposited using PECVD on the front side. Next, an e-beam resist (ZEP520A) is applied by spin-coating it onto the a-Si. The coated resist is then exposed using e-beam lithography (JEOL FS-6300) at 100 kV. After development using N50 developer, a 15 nm Cr₂O₃ layer is deposited via e-beam evaporation. To complete the process, the sample undergoes a lift-off process in PG remover at 80°C for 30 minutes. The pattern is then transferred into a-Si using ICP-RIE with a specific etching recipe (discussed in Chapter 4) to get a vertical profile. Lastly, the remaining hard mask is removed by dipping the sample into Cr etchant and rinsing it with DI water.

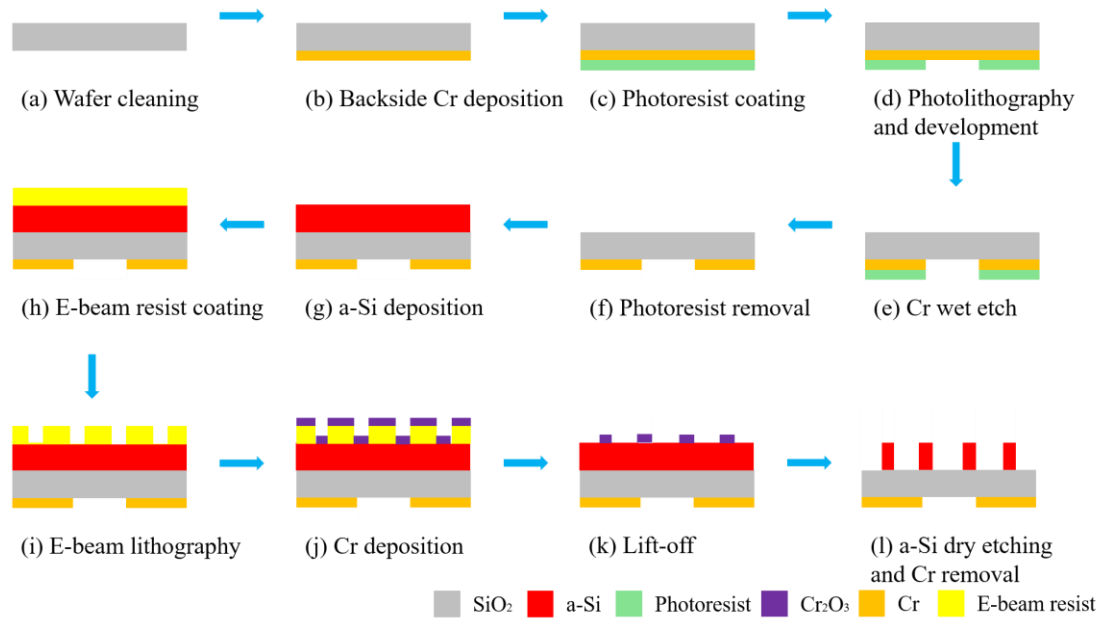


Figure 5.10. Process flow of metalens fabrication.

5.3.2 Characterization of metalens

Following fabrication, the metalens was initially inspected using an optical microscope and a scanning electron microscope (SEM). As shown in Figure 5.11, no significant defects were observed under the microscope. The SEM images, taken from both top and side views, clearly demonstrate that all pillars have a well-defined, round shape with smooth and vertical sidewalls. This achievement is a result of our highly customized etching recipes, as discussed in Chapter 4.

The schematic diagram of the constructed metalens testing system is presented in Figure 5.12. A narrow-linewidth laser with a wavelength of 940 nm serves as the incident light source and is connected to a fiber collimator for the testing system. This light source is positioned on a semicircular sliding rail that spans $\pm 90^\circ$, enabling the adjustment of the incident angle from 0° to 60° by moving the light source along the rail. The light, incident at various angles, illuminates the metal aperture located on the backside of the metalens sample substrate and subsequently passes through the

metasurface structure on the front side, resulting in a focal spot formed at different positions on the focal plane. The imaging system comprises an objective lens, a tube lens, and a Hamamatsu CMOS camera (C13440-20CU). By adjusting the imaging system in three-dimensional directions, the focal point can be precisely located, allowing for the capture of focal plane images of the metalens across various fields of view.

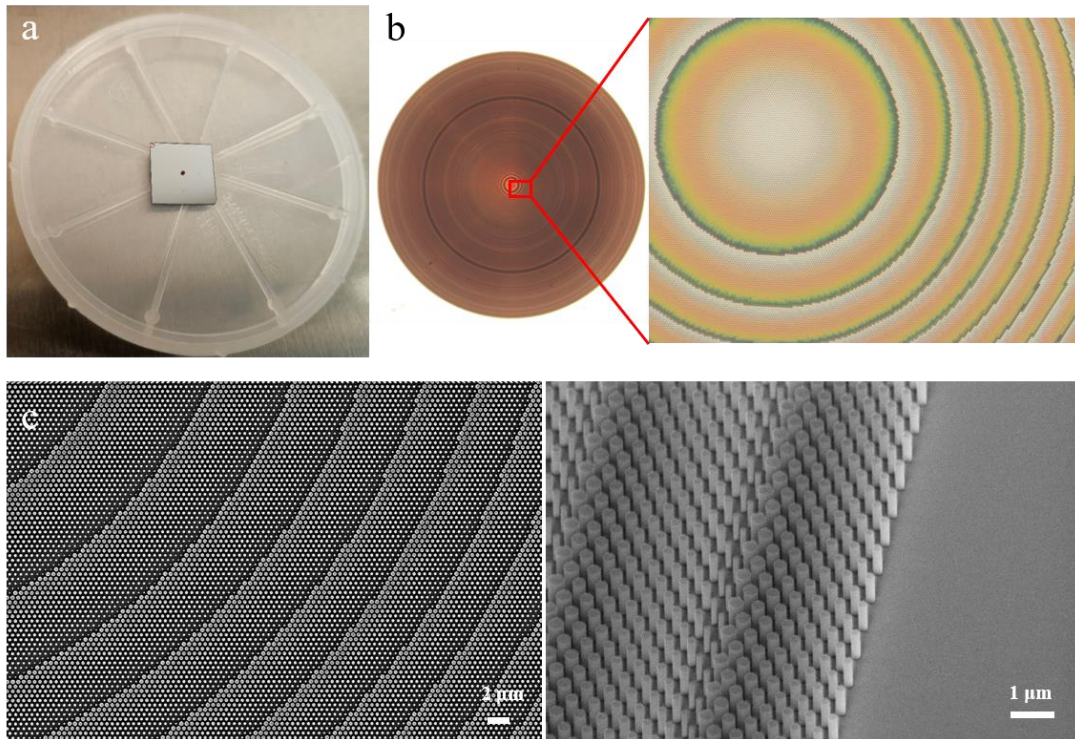


Figure 5.11. Fabricated metalens device. (a) Photograph of the device, with Cr coated on the backside and the metalens at the center of the frontside substrate. (b) Optical microscope image of the metalens. (c) SEM images of the metalens.

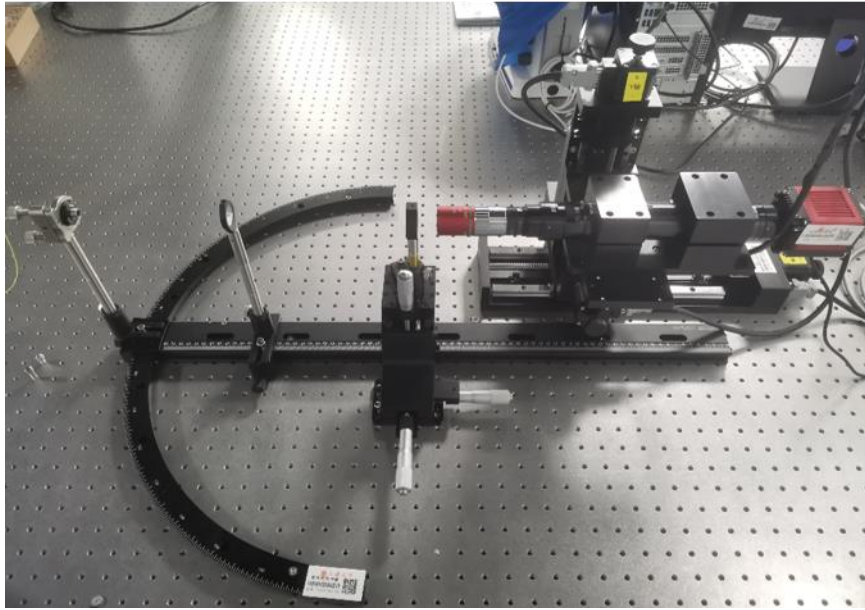
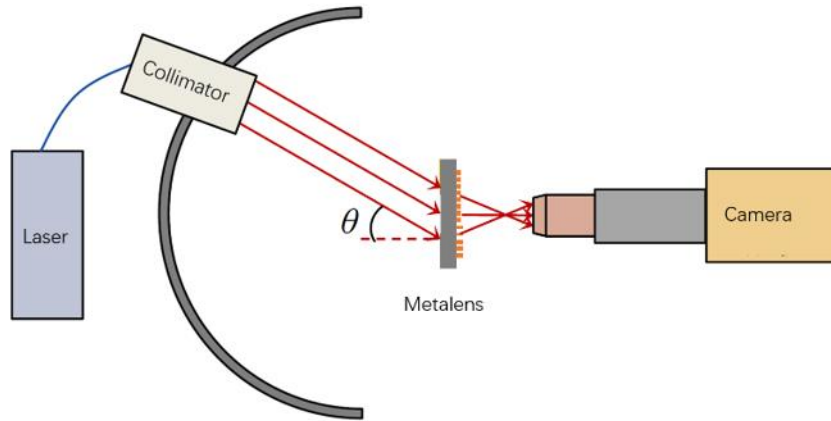


Figure 5.12. Schematic and photograph of the metalens testing system.

5.4 Results and Discussion

To begin with, the quality of the focal spot was analyzed for various incident angles. Figure 5.13 illustrates the normalized intensity distribution at the focal plane for incident angles ranging from 0° to 60° . It is evident that effective focusing is attained across all angles, with only minor distortion noticeable at an incident angle of 60° . These findings are consistent with the simulation results.

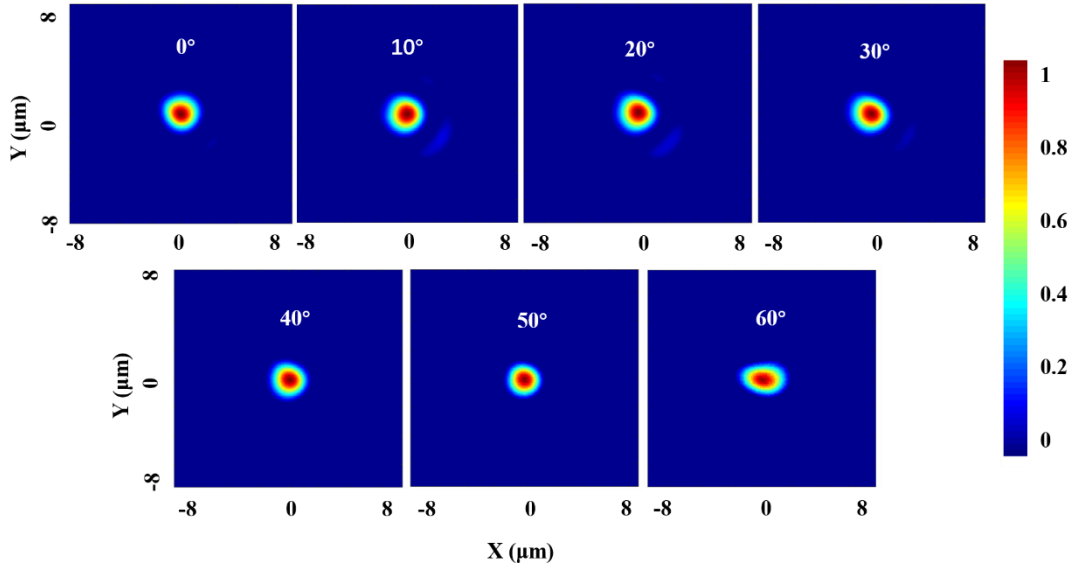


Figure 5.13. The normalized intensity distribution of the focal plane.

The measured focusing efficiency of the device at various angles is illustrated in Figure 5.14a. When the incident angle ranges from 0° to 20° , the focusing efficiency remains approximately 61%. However, as the incident angle exceeds 30° , the focusing efficiency starts to decline, dropping to 35% at an incident angle of 60° . The average focusing efficiency across the complete field of view is 51%. In comparison to the simulation results, the measured focusing efficiency is lower, likely due to increased scattering resulting from the sidewall roughness of the nanostructures at oblique incidence. By performing a Fourier transform on the intensity of the focal spot and taking its modulus, we obtained the MTF, and then calculated the SR, which characterizes the resolution of the lens. The SR is shown in Figure 5.14b. For incident angles between 0° and 50° , the SR remains above 0.8, suggesting diffraction-limited optical performance. Although the SR decreases at larger incident angles, the overall focusing performance remains commendable throughout the entire field of view.

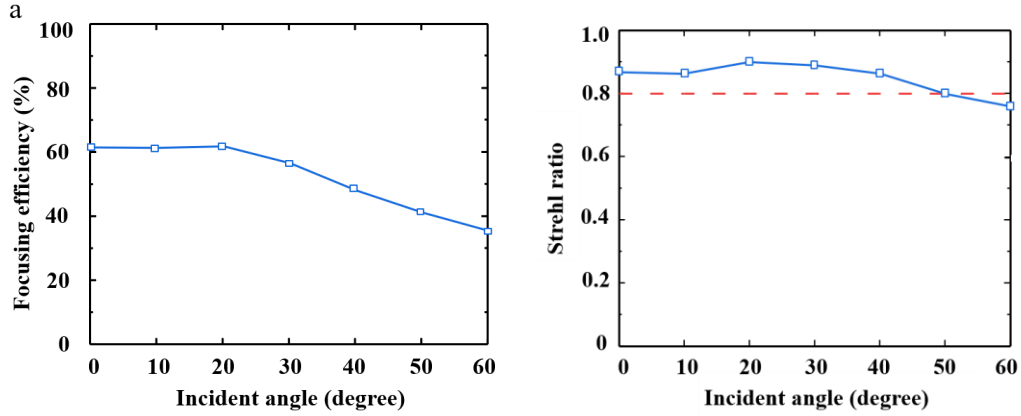


Figure 5.14. Experimental results of metalens device. (a) Focusing efficiency. (b) Strehl ratio.

5.5 Conclusion

In this study, we designed and implemented a large FOV metalens with an impressive total angular range of 120° at a near-infrared wavelength. A metal aperture was directly integrated into a fused silica substrate, enabling the separation of incident light from various angles, which was then directed onto distinct regions of the metasurface structure. This configuration achieved focused imaging at multiple positions along the focal plane. To optimize the phase profile of the metalens, we employed a ray-tracing algorithm, and the device was fabricated with meticulous process control and finely tuned recipes. No significant defects were observed, and the nanostructures exhibited an excellent profile. Following characterization, experimental results confirmed that the metalens maintains strong focusing performance across all incident angles, yielding an average focusing efficiency of 51%. The proposed near-IR metalens, characterized by its straightforward structure, expansive FOV, and high performance, holds significant promise for applications in facial recognition, laser radar, and medical imaging.

Chapter 6: Conclusion and future work

This thesis presents systematic studies on the design, fabrication, and application of dielectric metalenses. The main results are summarized as follows:

1. The defects introduced during fabrication can significantly affect the optical performance of metalenses, including focal spot intensity, focal length, and SR. Through a combination of simulations and meticulously designed experiments, we thoroughly examined the effects of four common defects: inclined SA, uniform CD bias, non-uniform CD bias, and notching effects. Our findings reveal that inclined SA has the most pronounced impact, resulting in an 11% intensity loss per degree. The notching effect is also important; it leads to a 12.5% intensity loss and a notable decrease in SR when as little as 4% of the pillars are missing. In comparison, uniform CD bias is less critical than inclined SA, causing a 5% intensity drop for every 10 nm deviation and only slight changes to focal length and SR. Non-uniform CD bias can sometimes be ignored to save time and costs, as it typically does not result in significant performance degradation.
2. Achieving vertical and smooth sidewalls in the nanopillars of metalenses is essential for optimal performance. The Bosch process and cryogenic etching techniques prove unsuitable for silicon nanopillar etching due to issues such as "scroll-like sidewalls" and crystal orientation-dependent etching. In this context, a non-switching mixed gas etching approach ($\text{C}_4\text{F}_8/\text{SF}_6$) has been identified as appropriate, although it typically results in a taper angle transition in the midsection of the pillars. To address this challenge, a multi-step ICP-RIE technique was developed. The result showed that the multi-step method offers enhanced control over both passivation and etching processes. By employing a continuous three-step etching strategy, we successfully fabricated both rectangular and circular HAR

nanostructures suitable for metalenses. This process enabled the creation of features as small as 70 nm with aspect ratios reaching up to 14. The remarkable controllability and adaptability of this method make it particularly well-suited for the fabrication of metalenses and other devices that demand precise HAR nanostructures.

3. Drawing on our investigation of fabrication-induced defects and the innovative multi-step plasma etching technique, we successfully developed a large FOV near-IR dielectric metalens. This metalens features a straightforward design that includes a metallic aperture integrated directly on the rear side of the substrate to direct the light. Our metalens achieves a total FOV of 120°, with an SR greater than 0.8 across all incident angles, except at 60°, demonstrating strong optical performance. Table 6.1 outlines the parameters of our metalens in comparison to other works. Notably, our metalens offers the largest FOV among these studies. While our focusing efficiency is reasonable and does not surpass that of designs with two components/metalenses, the single-layer configuration significantly simplifies the fabrication process and lowers costs, ultimately enhancing its overall performance relative to others.

Table 6.1 Comparison of Large FOV Near-IR metalenses

Works	FOV (°)	Wavelength (nm)	Components/ Metalenses	Focusing efficiency (%)
Engelberg et al. ⁷⁵	30	850	1	6-20
Arbabi et al. ¹³⁰	56	850	2	45-70
Xie et al. ¹³¹	120	830	2	41-57
This Work	120	940	1	35-61

In the future, further exploration can be conducted on other widely used metalens materials, such as TiO_2 and Si_3N_4 , to investigate fabrication-induced defects and identify appropriate etching methods. Additionally, altering the design of the large FOV metalens by employing different phase manipulation techniques, such as geometric phase, could enhance performance significantly.

In summary, the thesis makes a notable academic contribution to the design and production of a-Si metalens by serving as a comprehensive guide for process control. It demonstrates a structured research methodology and experimental verification, which has the potential to enhance both academic and industrial settings.

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