PHOTONICS INSIGHTS

Coevolution of nanophotonics and nanofabrication: achievements and beyond

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Recent advancements in nanofabrication techniques, coupled with innovative nanostructure designs, have unveiled intriguing possibilities for the manipulation of light. These capabilities encompass control over fundamental properties of light, including phase, amplitude, polarization, directional propagation, frequency conversion, chirality, and angular momentum of light. Unlike plasmonic nanostructures, which are often constrained by their inherent ohmic losses, dielectric metasurfaces, constructed from materials like titanium dioxide (TiO_2), silicon, and gallium nitride, offer low-loss and high-index alternatives[1–3]. This distinction allows for the development of more efficient and versatile optical devices[2–6], including lenses, holograms, structural color filters, and sensing platforms.

The advancement of nanophotonics and nanofabrication technologies can be likened to the coevolution of flowers and bees, with each evolving to meet the needs of the other. On the one hand, breakthroughs in nanofabrication enable the precise manipulation of various degrees of freedom of light at scales comparable to its wavelength in the visible spectrum[7,8]. This coevolution has led to the emergence of exciting fields in photonics, such as photonic crystals, plasmonics, and metasurfaces. In turn, the rapidly expanding applications of photonics not only fuel innovation in nanofabrication but also open transformative opportunities to enhance human life. As seen throughout the intertwined histories of biology and optics, many major biological innovations have been rooted in optical breakthroughs in the past hundreds of years. Today, nanophotonics, as the new frontier of optics, thrives on continuous advances in nanofabrication technology[9].

In the review article on the advanced manufacturing of dielectric meta-devices, as recently published in *Photonics Insights*, Yang *et al.*[10] offer an in-depth exploration into the latest advancements in metasurface fabrication technologies. This comprehensive overview highlights key nanofabrication methods, ranging from standard nanolithography techniques like electron beam lithography (EBL), focused ion beam (FIB) lithography, and laser-based nanolithography, to large-scale processes such as nanoimprint lithography and deep ultraviolet (DUV) lithography. While these techniques were originally developed and tailored many decades ago for the semiconductor industry, the demands of nanophotonics and metasurface fabrication often require new capabilities in handling and nanostructuring materials that are generally not complementary metal-oxide semiconductor (CMOS) compatible. The significance of these methods in fabricating high-resolution, high-aspect-ratio, and flexible metasurfaces paves the way for their applications in a broad array of optical devices.

The review underscores the importance of advanced nanofabrication techniques in achieving the intricate designs required for high-performance metasurfaces. Maskless lithography methods like EBL and FIB lithography, while highly precise, are limited by their scalability and high costs. Hence, they are best suited for prototyping and producing master patterns from which copies are made. The review emphasizes the necessity for scalable, cost-effective manufacturing techniques to transition metasurfaces from research labs to commercial applications. Replicating methods such as nanoimprinting and DUV lithography offer promising solutions by enabling wafer-scale production while maintaining the resolution needed for complex nanostructures.

In addition to highlighting the progress in fabrication techniques, the review also delves into the potential applications of dielectric metasurfaces. From structural color printing and holography to beam shaping and imaging, the versatility of these devices makes them suitable for a wide range of industries, including telecommunications, sensing, and consumer electronics. The review also mentions the growing interest in flexible metasurfaces, which could enable the integration of optical devices into wearable technologies and other non-planar surfaces.

Despite the promising advancements, the review importantly identifies several challenges that must be addressed to fully realize the potential of dielectric metasurfaces. One of the main hurdles is the scalability of fabrication processes, particularly when it comes to achieving uniformity and high throughput at the wafer scale. While techniques like DUV lithography and nanoimprinting offer solutions for large-scale production, further improvements in resolution, cost-efficiency, and production speed are necessary to meet the demands of commercial applications. Another challenge highlighted in the review is the need for better control over material properties and fabrication tolerances. As metasurfaces become more complex, the precision required to maintain consistent optical performance across large areas increases significantly. Advanced fabrication techniques must continue to evolve to meet these stringent requirements, particularly in applications where ultra-high resolution and narrow linewidth resonances are essential.

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Nanofabrication technology for 3D nanostructures with high refractive indices and high resolution is still in its infancy[11,12]. However, the ability to design in three dimensions offers more compact and versatile solutions for a range of photonic applications, particularly in photonic computing and topological photonics. As the field advances, it is foreseeable that large-scale, high-uniformity 3D nanostructures will attract increasing attention due to their greater flexibility in controlling light and their efficient spatial utilization. The demand for these structures is likely to grow as they offer new possibilities for next-generation photonic technologies.

From the perspective of future commercialization, it is likely that cleanrooms and production lines designed for photonic devices and chips will differ significantly from those currently used for CMOS technology, which are focused primarily on silicon wafers. In these next-generation photonic cleanrooms, electrical characteristics and testing will no longer be the primary focus. Instead, optical properties and the development of novel nanofabrication processes and advanced functional materials will take center stage[13–15]. As a result, we can anticipate greater investment and effort being directed toward photonic-specific cleanroom technologies and industries, accelerating the transition of innovative photonic devices from the lab to everyday life.

In conclusion, this review of advanced manufacturing techniques for dielectric metasurfaces provides a comprehensive and forward-looking perspective on the current state of the field. Although significant progress has been made in both the design and fabrication of metasurfaces, the path to commercialization remains challenging. Continued improvements in nanofabrication technologies, along with innovative advances in material science, will be key to unlocking the full potential of dielectric metasurfaces in next-generation photonic devices. Looking ahead, the ongoing coevolution of nanophotonics and nanofabrication technologies promises a sustainable and increasingly prosperous future for the field.

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