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Perspective

A Perspective on Shaping Matter with Light: Manufacturing Approaches for High-Resolution 3D Printing

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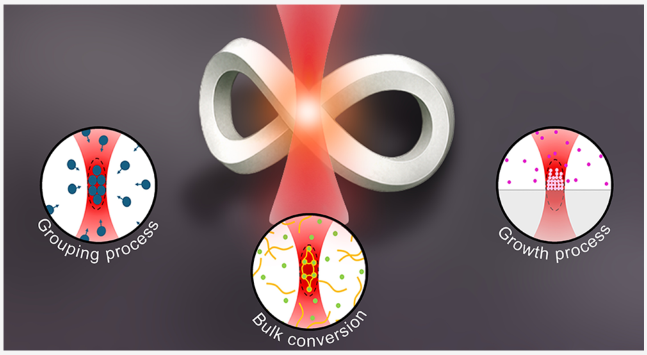
ABSTRACT: Advanced manufacturing processes have progressed rapidly in recent years in their ability to fabricate complex 3D structures. Most notably, light-based 3D printing processes have particularly stood out due to the various processes through which light-matter interactions can be spatially defined, a necessary criterion for high-resolution 3D printing. Here, we offer a perspective on the current state of light-based 3D printing at the micro- and nanoscale, highlighting recent works that exemplify the advances in terms of light delivery methods, processable material diversity, and cutting-edge applications. We follow this with a discussion of potential directions for furthering the potential of light-based 3D printing, pointing out what we see as largely unexplored avenues open for exploration in the field.



KEYWORDS: *laser direct writing, light−matter interactions, multiphoton polymerization, micro- and nanofabrication, inorganic materials, functional materials*

INTRODUCTION

Three-dimensional (3D) printing is transitioning from a niche prototyping tool into an emerging manufacturing technology. Unlike conventional subtractive or assembly based methods, fabricating objects directly from digital models removes geometric constraints and enables structures that would otherwise be difficult or impossible to realize, offering unprecedented design freedom. Light-based 3D printing[1] occupies a unique position by combining precise control over the properties of light with the ability to confine optical energy to extremely small volumes through tight focusing, thereby enabling spatially selective material transformations at the micro- and nanoscale.

The origins of light-based 3D printing lie in linear photochemical processes, where ultraviolet radiation drives polymerization in photosensitive resins, a principle that underpinned stereolithography, introduced in 1986 as a layer-by-layer 3D fabrication approach. The decisive step toward what is now recognized as high-resolution light-based 3D printing came with the introduction of ultrafast lasers in the late 1990s, which enabled nonlinear absorption processes. Through the quasi-simultaneous absorption of multiple photons, photochemical reactions normally induced by ultraviolet excitation can be confined to the focal volume, enabling submicrometer structuring even in otherwise difficult-to-access environments. Commonly referred to as two-photon polymerization or, more generally, multiphoton polymerization (MPP),[2] this approach now enables the maskless fabrication of complex 3D structures and has found broad application in optics, photonics, the life sciences, and related fields.[3]

Today, continued advances in laser technology, materials science, and our understanding of light−matter interactions have expanded light-based 3D printing to encompass a broader range of localized material transformations. Within tightly confined focal volumes, light can initiate threshold-driven photothermal, photochemical, and optically induced processes, enabling densification, crystallization, precursor decomposition, photoreduction, and nanoscale particle trapping. Today, these mechanisms extend light-based 3D printing to metallic, ceramic, and other inorganic architectures, opening new opportunities for manufacturing in photonics, microelectronics, sensing, and micromechanical systems.[4]

The growing diversity of light-induced material transformations has, however, given rise to an increasingly broad

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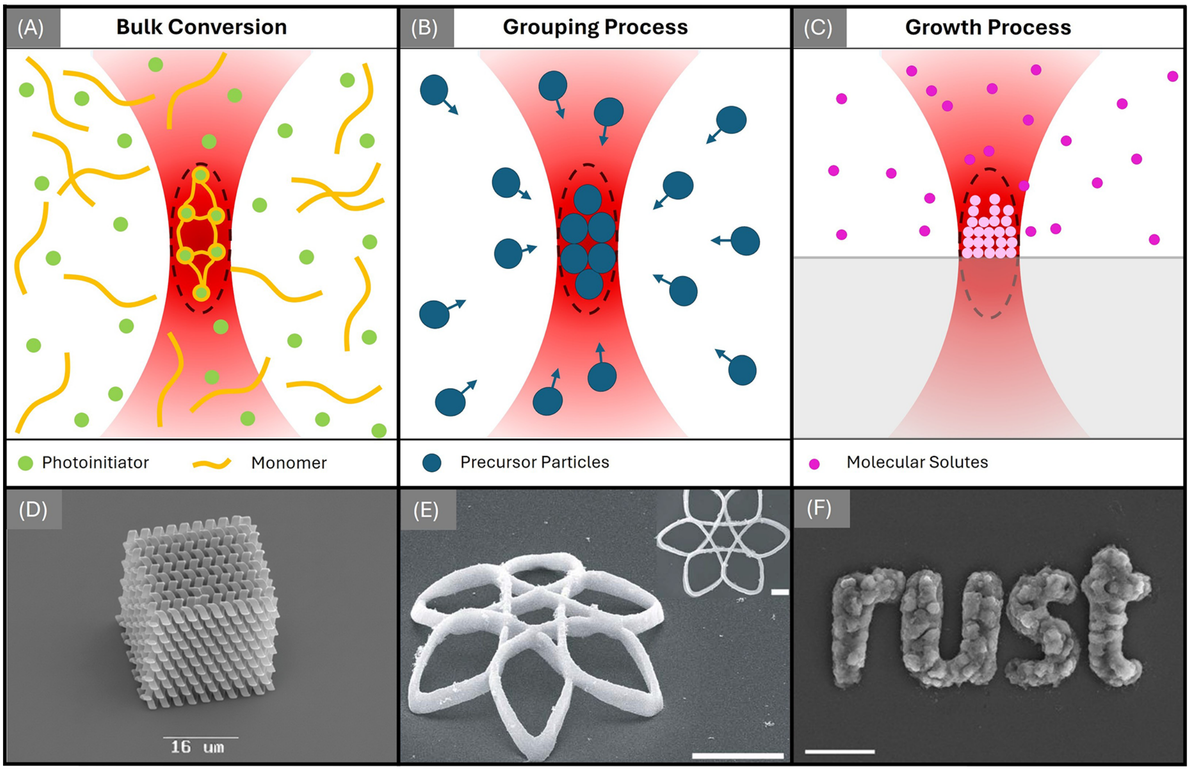

Figure 1. Voxel formation routes. (A) Schematic of a bulk conversion process depicting short-distance chemical bond formation and cross-linking within the volume of a laser focus. (B) Schematic of the grouping of particles within the volume of a laser focus. (C) Schematic of material growth on a substrate within the area of a laser focus. (D−F) Example printing results for each route,[5−7] reprinted with permission, copyright 2008 American Chemical Society,[5] copyright 2023 American Association for the Advancement of Science;[6] copyright 2016 American Chemical Society.[7]

and specialized range of high-resolution 3D printing approaches. This Perspective brings these developments together by organizing them according to the fundamental routes through which light directly shapes matter in three dimensions. Notably, we focus on processes that produce the final material during light exposure, excluding strategies that rely on additional material conversion through postprocessing steps. We examine the underlying physical mechanisms, fabrication strategies, and accessible material systems, and illustrate their current capabilities by highlighting selected applications. On this basis, we outline the key challenges and emerging opportunities that may guide the future development of high-resolution light-based 3D printing.

■ PRINCIPLES OF LIGHT-INDUCED VOXEL FORMATION IN 3D PRINTING

Understanding 3D printing requires considering how a 3D structure is built from smaller units. Similar to how a 2D image can be decomposed into pixels, a 3D object can be decomposed into volume elements (voxels). In both cases, the dimensionality of the object must be preserved.

As an image is a 2D object, its pixels are defined in 2D. In practice, pixels often have a rectilinear shape, e.g., as in microelectronic chips, where their edges are defined by the separation between electronically active pixel elements. In 3D printing, the shape and boundaries of a 3D voxel must likewise be defined. One may intuitively imagine voxels as perfect cubes. But how are such cubes formed or positioned in practice? In reality, the voxel shape in 3D printing depends on both the printing process and the target structure. This raises a central question: what defines the ultimate shape of a voxel?

The answer lies in the spatial confinement of material transformation within a defined volume, governed jointly by the light field and the material itself. Accordingly, in high-resolution light-based 3D printing, voxel formation relies on a nonlinear or discontinuous process that distinguishes the printed region from the surrounding unmodified material, while the underlying light−matter interaction determines the specific route through which matter is transformed into a voxel (see Figure 1), as described below.

One such route is *bulk conversion*, in which a voxel forms within a material volume upon light exposure, typically with only a small change in material density (see Figure 1A). Here, the voxel boundary is primarily defined by the spatiotemporal distribution of light intensity, without requiring material transport into the focal region. Bulk conversion is therefore the principal route for photopolymerization-based 3D printing and one of the most widely used approaches in the field, although it remains largely restricted to polymeric materials.

A second route, which offers access to nonpolymeric materials, is the localized *grouping* of particles through processes such as sintering or chemical bonding. These particles may either preexist in the printing medium or form in situ during exposure, with the voxel formation governed by diffusion as well as optical and convective forces that transport particles into the laser focal volume (see Figure 1B). However, the resulting structures may not be fully dense, as voids or pockets of trapped material can remain.

A third route comprises *growth* processes, which can yield high-quality nonpolymeric structures, potentially even with single-crystalline character. In this case, a voxel forms through material growth from a substrate or preexisting structure (see

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Figure 1C). While light defines the spatial extent of the growth region, voxel formation is primarily thermally driven and coupled to diffusion. The accessible material range is nevertheless constrained because the growing material must absorb sufficient optical energy to sustain growth away from the substrate.

Together, these three routes represent the principal mechanisms through which light directly forms solid voxels across different material classes. The following sections examine how these mechanisms are implemented in the light-based 3D printing of polymeric and inorganic materials and compare their respective capabilities and limitations.

■ LIGHT-BASED 3D PRINTING OF POLYMERIC MATERIALS

In light-based 3D printing of polymeric materials governed by bulk conversion, the delivered optical field is directly coupled to the photochemical response of the material, typically a photoresist, with the excitation profile, exposure dose, and nonlinear optical response collectively determine where polymerization occurs and how the resulting voxel is shaped.

Voxel formation is therefore governed by a nonlinear, threshold-driven absorption process involving radical generation, diffusion, quenching, and local heat transport. Light delivery into the excitation volume thus determines not only the location of material modification but also the confinement and geometry of the voxel, thereby controlling, e.g., feature resolution, structural fidelity, and throughput.

Femtosecond lasers are currently the leading technology for high-resolution light-based 3D printing, providing peak intensities in the TW cm^{-2} range required for nonlinear absorption in MPP. Continued advances in femtosecond laser technology, including optical parametric oscillators with tunable wavelengths and high peak powers, have broadened the applicability of MPP across a wide range of polymer systems, including acrylate and methacrylate photoresists, hybrid organic−inorganic and epoxy-based materials, and initiator-free systems.[8,9]

With strong focusing, typically using objective lenses with a numerical aperture of 1.4, lateral voxel sizes approaching 100 nm can be achieved. In practice, however, residual heating, radical diffusion, and excited-state absorption limit reliable feature sizes to approximately 200 nm and minimum voxel spacings to approximately 300−400 nm.[10] These limitations can be partly mitigated through grayscale exposure using laser power modulation, which provides local control over the exposure dose and enables dynamic voxel refinement to improve structural fidelity.[11]

Furthermore, the serial nature and high cost of tightly focused femtosecond laser writing significantly limit throughput and accessibility. To overcome these limitations, high-speed resonant and polygon scanners have been employed to increase sequential writing speeds, while spatial light modulators, microlens arrays, and metalenses enable parallel multifocus exposure at rates of up to 1.4×10^8 voxels per second.[12] Digital micromirror devices provide an additional route to higher-throughput fabrication through projection-based spatiotemporal focusing,[13] in which spectral dispersion confines the peak intensity to the focal plane and suppresses out-of-focus polymerization.

Addressing the cost barrier, high-repetition-rate GHz diode lasers exploit cumulative material excitation across successive pulses to sustain polymerization at lower peak intensities while achieving speeds and resolutions comparable to conventional MPP.[14,15] Cascade upconversion schemes provide another route by relying on nonlinear optical processes within the material rather than nonlinear excitation by the light source. In these systems, nanoparticles convert near-infrared continuous-wave illumination into higher-energy emission that drives polymerization.[16]

Two-step absorption offers a further route toward accessible high-resolution 3D printing, in which a molecule is first excited into a long-lived intermediate state from which a second low-power photon triggers polymerization. Recent demonstrations using compact 405 nm diode lasers have achieved sub-200 nm voxel sizes,[17] and combined with DMD-based holography, fabrication rates of up to 61,500 voxels per second, placing this approach on par with conventional MPP at a fraction of the system complexity and costs.[18]

Compact and highly parallel light delivery can also be achieved through holographic tomographic volumetric additive manufacturing, which combines compact laser sources with amplitude- or phase-modulation-based light engines.[19] Here, computer-generated holograms project light into a rotating resin vat, where the dose accumulates from multiple angles until the polymerization threshold is reached. This enables volumetric fabrication without voxel-by-voxel scanning,[20] although the achievable resolution does not yet extend into the submicrometer regime.

■ LIGHT-BASED 3D PRINTING OF INORGANIC MATERIALS

Alongside bulk conversion, grouping and growth processes are essential for the direct light-based 3D printing of inorganic materials, offering substantial potential for high-performance functional devices with properties that are difficult to achieve using conductive or semiconducting polymers. For example, light exposure can induce the photochemical reduction of metal salts and complexes through photon-driven electron transfer, generating zerovalent metal species that nucleate, grow into nanoparticles, and assemble into conductive structures.[21] Femtosecond lasers are particularly well suited to these processes because multiphoton absorption confines the reaction to the focal volume and improves spatial selectivity, enabling direct reduction of noble-metal precursors such as Ag, Au, Pd, and Pt, while Cu, Ni, and Co typically require additional reducing agents; ligand chemistry and functional additives offer further control over electron transfer.

In photoreduction, however, the low concentration of metal-containing species is typically insufficient to form a cohesive voxel through reduction alone. The initially formed nanoparticles must therefore be assembled by laser-induced optical forces and sintered through local heating, constituting a grouping process.[21] Following this strategy, careful precursor design has enabled the printing of metals such as Mo, Co, and W, as well as Mo−Co−W alloys, through two-photon decomposition, optical trapping, and nanocrystal sintering.[22] Precursor and solvent selection is, however, critical for efficient metal formation while limiting heat accumulation and parasitic reactions. The accessible material range therefore remains narrow, and achieving complex architectures or subdiffraction resolution requires careful control of photochemical and photothermal reduction through precursor chemistry, solvent viscosity, heat dissipation, and mass transport. Nonetheless, feature sizes of several hundred nanometers, including Mo lines approaching 100 nm, have been demonstrated,[22] while

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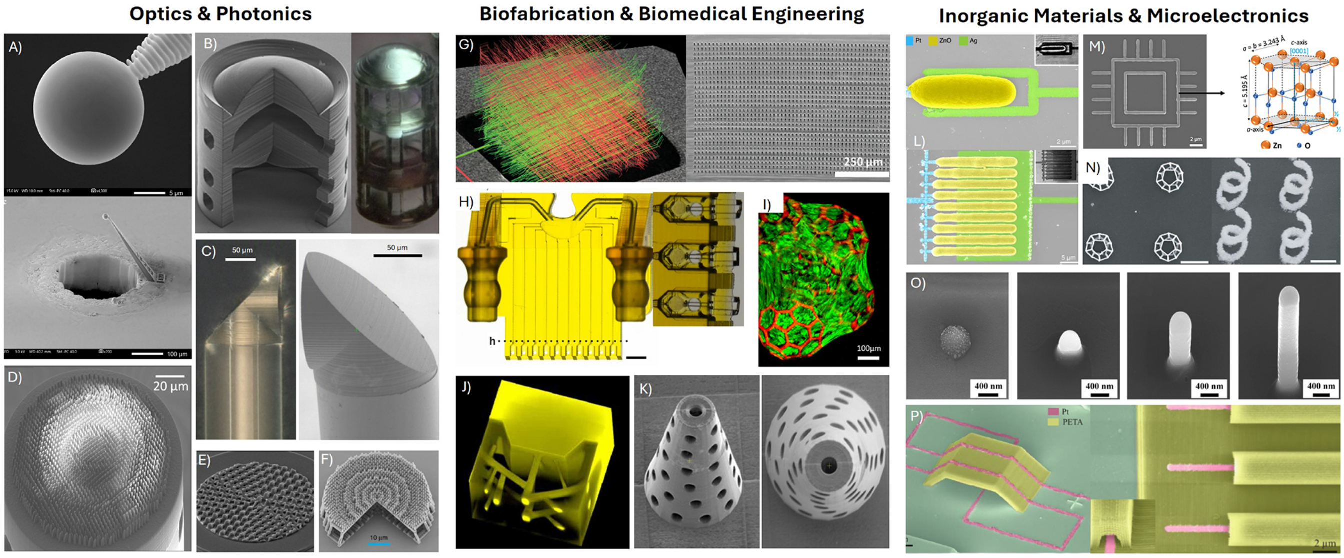

Figure 2. Applications of high-resolution light-based 3D printing. Optics and photonics: (A) optical microsphere devices,[11] (B) multilens microoptics,[38] (C) total internal reflectance endoscope,[39] and (D−F) flat-optics and achromatic metalenses.[40−42] Biofabrication and biomedical devices: (G) diffusion MRI brain phantom,[34] (H) nanoliter perfusion system for in vitro fertilization,[43] (I) scaffolded cellular spheroids,[44] (J) microvascularized organ-on-chip platform,[45] and (K) porous microneedles.[30] Inorganic materials and microelectronics: (L) Pt−ZnO−Ag memristive heterojunction diodes,[37] (M) single-crystal ZnO structures,[24] (N) nanocrystal-assembled TiO_2 and chiral Au nanorod helices,[6] (O) high-aspect-ratio Si pillars,[25] and (P) isolated 3D metallic interconnects.[36] Examples reprinted with permission under CC BY 4.0[11,24,34,36−41,43−45] (https://creativecommons.org/licenses/by/4.0/), copyright 2026 American Chemical Society,[42] copyright 2023 Wiley-VCH GmbH,[30] copyright 2023 American Association for the Advancement of Science,[6] copyright 2025 Elsevier.[25]

scan speeds for these grouping processes remain limited to a few micrometers per second.

Starting from nanoparticle solutions rather than molecular precursors bypasses in situ material formation, as femtosecond lasers can directly assemble preexisting nanoparticles through sintering or chemical bonding while confining voxel formation through two-photon absorption or hot-electron generation.[23] This approach potentially extends the printable material range to nearly any available nanoparticle system and enables feature sizes below 300 nm,[6,23] provided that the particle dimensions remain well below the laser wavelength to minimize scattering. Still, as noted above, grouping preexisting nanoparticles often introduces microscopic voids or trapped impurities, which may account for up to 10% of the resulting structure.

Considering grouping and growth processes more broadly with respect to the excitation source, inorganic 3D printing does not necessarily require femtosecond lasers. Longer-pulsed and continuous-wave sources can, for example, drive photothermal reactions by locally heating the substrate and surrounding solution, causing dissolved precursors to decompose and precipitate as metallic or oxide structures.[7] Depending on the precursor and processing conditions, voxel formation may proceed through nanoparticle generation and aggregation or through epitaxial growth from the substrate. The latter can yield single-crystalline structures, as demonstrated for ZnO[24] and Si,[25] with voxel dimensions determined by the laser focal volume, exposure time, and the thermal properties of both the substrate and the surrounding solution. Growth-based approaches nevertheless remain less common because material formation must be confined to an existing surface, whereas many precursors preferentially form nanoparticles that subsequently require grouping.

Furthermore, nanoparticle solutions can be used in photothermal printing, where laser-induced temperature gradients generate bubbles and convective flows rather than directly driving chemical transformation. In bubble-assisted direct laser writing, femtosecond irradiation generates Ag nuclei and microbubbles through nonlinear photochemistry and localized heating.[26] Marangoni convection at the bubble interface then transports nanoparticles toward the rear of the bubble, enabling continuous writing of hierarchical nanoparticle layers with feature sizes below 10 μm at scan speeds of a few micrometers per second.

By contrast, convective flows can guide the deposition of preexisting nanoparticles,[27] which are subsequently fixed through sintering or intermolecular interactions to yield feature sizes down to the submicrometer scale. As such, this fabrication approach uniquely combines two-photon processes, thermally driven fluid dynamics, optical trapping, and photothermal sintering, providing a versatile route to the 3D printing of complex inorganic structures from diverse material systems, including SiO_2, TiO_2, and Fe_2O_3 nanoparticles.

■ APPLICATIONS OF HIGH-RESOLUTION LIGHT-BASED 3D PRINTING

Owing to the versatility of current fabrication strategies and material systems, high-resolution light-based 3D printing has progressed beyond rapid prototyping toward the direct fabrication of functional devices. Still, among the voxel-formation routes discussed, many application-oriented demonstrations rely on bulk conversion processes, particularly MPP, which has gained widespread use across multiple research fields.

In this context, optics and photonics rank among the most prominent application areas of MPP because nonlinear excitation enables direct writing at nearly any optically accessible location, including on optical fibers and photonic chips. This capability supports the fabrication of compact components for light manipulation, optical coupling, and controlled light transfer.[28,29] It is further complemented by the

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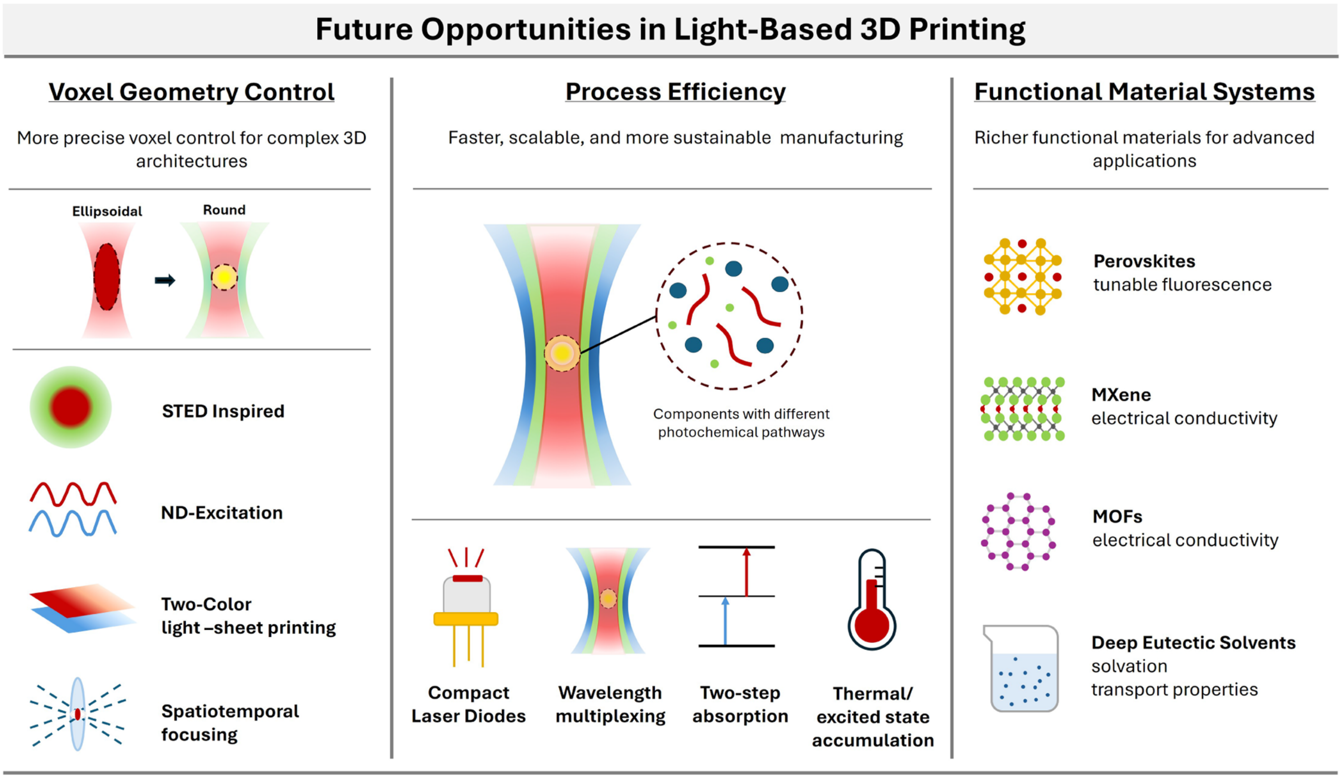

Figure 3. Future opportunities in high-resolution light-based 3D printing. Voxel geometry control for improved printing precision (left), process efficiency for faster and more sustainable manufacturing (center), and functional material systems for advanced applications (right).

optical properties of commonly used photoresists, whose refractive indices typically range from approximately 1.45 to 1.60 and are therefore comparable to those of standard optical polymers and glasses. Combined with the ability to realize near-arbitrary free-form geometries across length scales from the microscale to the millimeter scale, MPP enables the high-fidelity fabrication of both micro- and macro-optical elements (see selected examples in Figure 2A−C), allowing device footprints to be reduced and sophisticated optical phenomena to be exploited.

One such example is the use of photonic nanojets to enhance lateral resolution beyond the classical diffraction limit. Here, MPP combined with grayscale exposure has been used to fabricate microspheres with near-perfect sphericity and exceptionally smooth surfaces on preprocessed substrates containing apertures that guide light onto the spheres, enabling microsphere-assisted microscopy with numerical apertures exceeding 1 without immersion media.[11] Beyond micro-optical elements with relatively simple geometries, MPP enables the fabrication of sophisticated nanoscale photonic structures on a wide range of substrates whose functionality arises from their spatial arrangement, thereby providing an effective route toward manufacturing flat optical elements and metasurfaces for compact and highly integrated optical systems (see selected examples in Figure 2D−F).

Alongside optics and photonics, MPP is emerging as an enabling technology in medicine and biomedical engineering, progressing toward clinically relevant applications through its ability to fabricate complex 3D architectures with the precision required to mimic biological tissues, while also allowing patient-specific customization (see selected examples in Figure 2G−K). In biofabrication, current efforts include tissue constructs for repair and replacement, functional microneedles,[30] tailored prostheses, and vascularized networks,[31] with precise control over the 3D cellular microenvironment to affect cell behavior and fate.[32] Another promising direction is organ-on-chip technology, which combines microfluidics with 3D cell culture to reproduce physiological tissue environments for disease modeling, drug screening, and toxicity testing, thereby offering potential alternatives to conventional animal experiments.[33] Biomedical applications also extend to clinical and diagnostic technologies, ranging from medical-imaging phantoms[34] to specialized micro-optics for cellular and tissue imaging.[35]

Complementing polymer-based applications, light-based 3D printing of inorganic structures provides access to advanced functionalities, including high electrical conductivity, semiconducting behavior, crystallinity, and catalytic activity, thereby opening opportunities in photonics, catalysis, and energy storage and conversion technologies (see selected examples in Figure 2L−P). In this context, grouping-based approaches assemble colloidal nanocrystals as preformed functional building blocks into inorganic 3D architectures.[6] By contrast, growth-based approaches allow single-crystalline Si nanostructures, such as pillars and wires, to be directly laser-written from liquid cyclohexasilane.[25]

Among these opportunities, microelectronics currently stands out as a particularly compelling application area for light-based 3D printing of inorganic materials, as electronic devices often require insulating, conducting, and semiconducting materials to be integrated within a single architecture. Sequential multimaterial approaches have addressed this requirement by combining polymer structures with directly written conductive metal lines.[36] More recently, two-photon reduction and photothermal growth were combined to print Ag, Pt, and ZnO in three sequential steps, enabling the

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fabrication of functional devices such as diodes, memristors, and physically unclonable arrays.[37]

FURTHER OPPORTUNITIES AND PERSPECTIVES

Despite its growing relevance across a diverse range of applications, high-resolution light-based 3D printing remains less established than other manufacturing technologies operating at comparable length scales, including photolithography, soft lithography, casting, and injection molding.

Among the light-based 3D printing approaches presented here, only MPP has currently reached a high level of technological maturity, supported by decades of development, commercially available systems, and tailored photoresists and processing strategies, although considerable room for further improvement remains. Notably, MPP can be combined with postprocessing steps such as pyrolysis, infiltration, deposition, or calcination, which also enable the production of inorganic and other functional materials.[46] However, these additional steps can reduce the versatility of light-based 3D printing by causing shrinkage, constraining material and substrate compatibility, and complicating flexible multimaterial integration. In view of these and other limitations discussed further below, grouping- and growth-based processes may offer promising complementary routes for the fabrication of functional inorganic 3D structures by enabling the target material to form directly upon light exposure and may therefore become increasingly important when such materials must be fabricated with high resolution at specific locations.

Looking ahead, continued progress in high-resolution light-based 3D printing will be needed to advance its overall technological maturity, realize its full potential, and thereby create new possibilities for the development of cutting-edge technologies. We anticipate that key aspects of progress along this path will include greater control over voxel geometry, higher process efficiency, and broader access to functional material systems (see Figure 3). In the following, we elaborate on opportunities and strategies for advancing these areas, which may help strengthen the competitiveness of light-based 3D printing relative to established high-resolution manufacturing technologies and make its distinctive combination of geometric complexity, miniaturization, and advanced material integration more widely accessible.

Control over Voxel Geometry

The size and shape of the voxel fundamentally constrain the geometries that can be achieved through 3D printing. For example, in bulk conversion 3D printing processes, particularly in MPP, thresholding effects, as described above, enable lateral feature sizes of 100 nm or below; however, this improvement primarily applies to the lateral dimension. The asymmetric intensity distribution within the focal region produces ellipsoidal voxels that are elongated along the optical axis, typically with aspect ratios of approximately 2.5 and, in many cases, even higher. Consequently, voxel anisotropy makes structures requiring high geometric fidelity in the nanoscale to low-micrometer regime, such as perfect spheres, ideal 3D photonic crystals, and low-loss waveguides, particularly challenging to fabricate.

To improve spatial resolution at the voxel level, stimulated emission depletion, in some cases combined with chemical quenchers, has been successfully demonstrated in MPP[47,48] and could, in principle, be adapted to other bulk conversion 3D printing processes. By employing a secondary laser to spatially suppress polymerization within selected regions of the excitation volume, this approach can reduce feature sizes in MPP by up to a factor of 2. However, the technique relies on specifically engineered photoresists, which restricts material flexibility and limits its broader applicability.

An alternative strategy is to selectively promote reactions only in regions where multiple light beams overlap, thereby shaping the voxel geometry. This principle has been demonstrated in light-sheet 3D printing using two-color, two-step absorption[49] and could potentially be extended to MPP by employing femtosecond laser beams of different wavelengths to enable nondegenerate multiphoton excitation, which involves the quasi-simultaneous absorption of photons with different energies. As demonstrated in two-photon microscopy,[50] this mechanism confines nonlinear excitation to the spatiotemporal overlap region of the beams and could therefore provide greater control over voxel confinement and geometry.

To avoid introducing a secondary laser into the printing process, and thereby increasing the technical complexity of an optical setup, one could instead exploit the multiple wavelengths inherently present in ultrashort laser pulses. This concept has already been realized for spatiotemporally focused light sheets in 3D printing and has also been demonstrated for single-focus shaping in the context of subtractive manufacturing,[51] even allowing for producing round voxel shapes.[52]

The use of multiple light beams, multiple wavelengths, and spatiotemporal control over optical energy deposition may also be relevant to grouping and growth processes. Achieving finer features in these processes would, however, likely require tighter control over thermal gradients and localized heating during printing. Pulsed lasers may be particularly suitable in this context, as they enable both temporal shaping of the heating profile and highly localized energy deposition, with recent demonstrations of ultrafast heating[23] suggesting a potential route toward more precise control over material deposition and localized sintering.

Process Efficiency

While recent advances have sought to improve the scalability of MPP,[53] they have often come at the cost of increased system complexity and expense, particularly with respect to the laser source. As mentioned before, GHz diode lasers emitting picosecond pulses offer a promising route to addressing this challenge,[14,15] potentially enabling diode-array configurations for parallel exposure, substantially lower system costs, and tabletop MPP printers. Fully exploiting such laser sources, however, requires a deeper understanding of the underlying physical mechanisms. In particular, scalability limitations arising from dose-accumulation effects must be considered, with thermal accumulation and excited-state absorption remaining generally underexplored in MPP as potential mechanisms for improving printing efficiency. Efforts to integrate dynamic optical characterization[54,55] could provide the understanding required to harness these effects systematically.

Another particularly promising route toward improving the efficiency of bulk conversion processes is the identification of more efficient light-matter interaction mechanisms.[56] 3D printing of polymeric materials based on two-step absorption represents an important development in this direction.[17] However, more suitable photoinitiators and reaction pathways must still be identified to broaden the applicability of this approach. Recent work on novel photoinitiators demonstrates progress in this regard.[57]

Similarly, photothermal printing processes stand to benefit from the identification of precursors or additives that enable material deposition at lower decomposition temperatures, thereby reducing laser power requirements and broadening compatibility with multimaterial printing architectures. On the laser side, selecting a wavelength that maximizes absorption can further reduce the laser power required for photothermal conversion. However, the fabrication speed of most inorganic-material printing processes is fundamentally constrained by the diffusive transport underlying grouping and growth, typically limiting deposition rates to the micrometer-per-second range. Reducing the required laser power could still facilitate the implementation of highly parallelized light-delivery schemes, such as multifoci exposure[12] or high-resolution projection-based printing,[58] both of which have been successfully demonstrated in MPP.

Looking further ahead, wavelength multiplexing could offer an elegant route toward more versatile multimaterial processing, beyond its role in controlling voxel geometry. By tailoring each wavelength to the optical properties and photochemical response of a specific material, various materials could be processed selectively and efficiently within a single system.[59]

Functional Material Systems

In addition to the challenges in physics, optics, process development, and system engineering addressed in the preceding sections, expanding the range of accessible functional materials presents a complementary challenge at the interface of materials engineering and chemistry that will be essential for realizing the full potential of high-resolution light-based 3D printing. In particular, such materials could enable direct control at the voxel level over local composition, conductivity, crystallinity, and optical properties without the need for postprocessing.

Within bulk conversion processes, halide-perovskite-based photoresists provide a compelling example of how such functionality can be realized.[60] Under femtosecond laser irradiation, polymerization of the resist matrix and crystallization of the perovskite precursors can occur simultaneously, yielding fluorescent structures with tunable emission in a single fabrication step and thereby enabling the direct fabrication of spectrally programmable photonic devices.

For electronic functionality, alongside conductive composites based on PEDOT:PSS,[61] MXene-containing photoresists offer a further promising route toward directly printed functional electronics by enabling highly localized patterning of conductive features at the voxel level.[62]

Deep eutectic solvents represent another promising class of functional material systems for bulk conversion processes[63,64] as their tunable precursor compositions provide opportunities for targeted materials engineering and may enable the direct fabrication of 3D architectures from metals and alloys.[65]

Metal−organic frameworks, in turn, address a distinct set of functional requirements by combining controlled porosity with spatially programmable surface chemistry, making them particularly relevant to sensing, catalysis, and gas-adsorption applications.[66] Notably, metal−organic framework nanoparticles or their precursor solutions could potentially be incorporated into growth-based and multimaterial printing strategies to produce structures with high material purity and tailored functionality.

More broadly, combining growth-based printing with multimaterial approaches may enable the localized selection, growth, and doping of materials within 3D crystalline architectures, while advances in ink and precursor formulations could further reduce fabrication complexity by allowing multiple materials to be selectively addressed within a single printing process. Such capabilities could ultimately support complex 3D device architectures for electrical sensing and computing that overcome some of the geometric and material limitations of conventional 2D photolithography.

■ CONCLUSIONS AND OUTLOOK

This Perspective has outlined the current landscape of high-resolution light-based 3D printing while highlighting selected directions with substantial potential to advance the field. Looking further ahead, it will be particularly interesting to see whether emerging chip-scale femtosecond laser sources can be applied to high-resolution 3D printing,[67] whether recently proposed 3D holographic light-shaping strategies can overcome current limitations in printing speed,[68] and whether further advances in controlling concentration gradients, precursor chemistry, and microscale fluid forces can enable efficient and flexible multimaterial printing.[27] As light-based 3D printing gains relevance across an expanding range of scientific and technological fields, continued progress in light sources, material systems, and fabrication strategies is expected to extend its capabilities and broaden its impact. We hope that this Perspective provides a useful framework for navigating this rapidly evolving field and encourages researchers across disciplines to address the remaining challenges and explore the many possibilities ahead.

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