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Advances in Ultrafast Laser Micro-/Nanofabrication and Its Applications in Optoelectronic Devices

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Abstract. Owing to their ultrashort pulse duration and high peak power, ultrafast lasers enable the fabrication of micro-/nanostructures and the localized tailoring of material properties in a wide range of materials through strong nonlinear absorption, with a limited heat-affected zone. This paper reviews four representative approaches—laser ablation, femtosecond laser direct writing, laser-induced periodic surface structures, and two-photon polymerization—focusing on their applications in photodetection, photovoltaics, light-emitting devices, integrated optics, and emerging optoelectronic materials. Ultrafast lasers can improve optical responses through surface light trapping and refractive-index modification, and tailor material functionality through defect engineering or doping. Nevertheless, laser processing may also increase dark current, enhance interfacial recombination, induce thin-film cracking, and raise propagation loss. The principal challenges include limited processing throughput, poor process transferability, material damage, and the absence of standardized evaluation protocols. Applicability will require beam shaping and parallel processing, strengthened in situ monitoring and process-data collection, and integration with conventional micro-/nanofabrication.

Keywords: ultrafast laser, micro-/nanofabrication, optoelectronic devices, femtosecond laser direct writing, laser-induced periodic surface structures

1. Introduction

Optoelectronic devices are evolving toward miniaturization, flexibility, and integration, and their performance depends on optical-field management and material control at the micro- and nanoscale. Surface structures primarily govern reflection, absorption, and light-extraction coupling, whereas defects, dopants, and interfacial states within a material determine carrier generation and transport. Micro-/nanofabrication techniques capable of both structural fabrication and functional definition have therefore become essential for improving device performance.

Conventional photolithography and its associated etching and deposition processes are well established, but they involve complex, mask-dependent workflows. For sensitive material systems such as perovskites and two-dimensional (2D) materials, these processes may introduce contamination or interfacial degradation; they are also limited in three-dimensional (3D) processing inside transparent materials and in rapid prototyping. Ultrafast lasers deposit energy locally through femtosecond or picosecond pulses, enabling surface ablation, bulk modification, and maskless

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patterning [1-3]. Laser-induced periodic surface structures (LIPSS) can further tailor absorption, polarization, and interfacial functionality [4]. These techniques have been applied to black-silicon photodetectors, transparent-electrode patterning, enhanced light extraction from light-emitting diodes (LEDs), and direct writing of glass waveguides, and are increasingly being extended to 2D-material and perovskite devices [5-13]. This paper sorts representative research achievements, analyzes processing principles, performance improvement and material damage side effects, and summarizes universal problems in various application scenarios.

2. Processing principles and representative methods

Ultrafast laser-material interactions are characterized by nonequilibrium dynamics, strong spatial localization, and the coupling of multiple mechanisms. When a high-intensity ultrashort pulse is focused onto or inside a material, energy is transferred through linear or nonlinear absorption, followed by ionization, electronic excitation, and plasma formation. Subsequent processes may include melting and resolidification, ablation, refractive-index modification, or phase transformation. In transparent media and wide-bandgap materials, nonlinear absorption confines modification to the focal region, thereby supporting the inscription of embedded waveguides and 3D structures. In metals and semiconductor thin films, localized energy deposition can instead produce micropores, grooves, or periodic textures [1, 3].

Compared with continuous-wave or nanosecond lasers, ultrafast pulses deposit energy faster than significant thermal diffusion can occur, and reduce the heat-affected zone. However, "ultrafast" does not imply "damage-free." Processing outcomes are jointly determined by the spatiotemporal pulse parameters, focusing conditions, and ambient environment. High repetition rates can cause heat accumulation, whereas excessive fluence may induce melting, cracking, or interfacial delamination. Processing quality should be assessed by structure formation or resolution, and by optical, electrical, and reliability metrics.

Four techniques are particularly relevant to optoelectronic-device fabrication. Laser ablation and surface microstructuring produce micropores, grooves, or roughened layers for antireflection, light trapping, and electrode isolation. Femtosecond laser direct writing uses refractive-index modification or selective material removal to fabricate waveguides and 3D optical circuits in transparent materials [3, 12]. LIPSS employ polarization-dependent surface electromagnetic fields to form subwavelength periodic textures for tailoring optical responses and interfacial properties [4]. Two-photon polymerization relies on nonlinear absorption at the focal point to fabricate complex 3D structures and is widely used for micro-optical components and photonic crystals [9]. These methods emphasize morphological control, material-property modification, or 3D writing, and can be combined within a single device.

3. Applications in optoelectronic devices

3.1. Photodetectors and solar cells

Both photodetectors and solar cells depend on optical absorption and the generation and collection of charge carriers. Ultrafast lasers can create multiscale textures on silicon and other semiconductor films, causing multiple scattering and increasing the effective optical path length. Carey et al. reported femtosecond-laser-microstructured silicon photodiodes with broadband responsivity from the visible to the near-infrared region [5]. Tao et al. fabricated an Au-hyperdoped black-silicon photodetector using a femtosecond laser; its near-infrared response was enhanced by both

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geometrical light trapping in surface conical structures and impurity-induced intermediate energy levels [6]. These studies show that ultrafast lasers can modify not only surface morphology but also defect states and band structure.

In solar cells, laser texturing is primarily used for light management and electrode optimization. Direct laser interference patterning of transparent conductive films such as indium tin oxide (ITO) can tune surface scattering and transmission while retaining useful electrical conductivity [10]. Enhanced absorption, however, does not necessarily translate into higher device efficiency. Defect states in a photodetector may broaden its spectral response but also increase dark current; similarly, texturing in a solar cell may raise the short-circuit current while damaging the passivation layer and intensifying interfacial recombination. Performance should therefore be evaluated using optical, electrical, and stability metrics rather than surface morphology or a single optical parameter.

3.2. Light-emitting and integrated-optical devices

A fraction of the light generated in LEDs and organic LEDs (OLEDs) remains trapped inside the device owing to total internal reflection and waveguide modes. Ultrafast lasers can create light-extraction structures on device surfaces or encapsulation layers, thereby altering the angular emission distribution and improving extraction efficiency. Chang et al. fabricated micro-/nanostructures on the ITO surface of GaN-based LEDs, demonstrating that noncontact surface modification can enhance light extraction [11]. Compared with wet etching, laser processing offers greater pattern flexibility and a shorter process flow. Nevertheless, surface roughness and electrode integrity must be carefully controlled; otherwise, the optical gain may be offset by increased contact resistance and localized current crowding.

Integrated optics emphasizes selective 3D writing inside transparent materials. Davis et al. inscribed optical waveguides in glass, establishing the basis for femtosecond-laser fabrication of embedded optical circuits [12]. This maskless method is suited to the rapid fabrication of passive components and 3D interconnects and, when combined with post-processing, can produce hollow channels or optofluidic structures. Its principal constraints are propagation loss, mode matching, and fabrication consistency. Optimization must move beyond writability toward low-loss, packageable, and scalable devices.

3.3. Devices based on emerging optoelectronic materials

Emerging optoelectronic materials impose more stringent requirements for low-damage, localized, and maskless processing. Femtosecond lasers can pattern and locally tailor graphene and transition-metal dichalcogenides and have been used to fabricate field-effect transistors, p-n junctions, and photodetectors [7]. Enrico et al. demonstrated noncontact, resist-free nanopatterning of 2D materials, highlighting the potential for rapid and clean processing [13]. However, atomically thin layers have an extremely narrow processing window, and both thermal effects and edge defects can alter the final electrical properties. Minimum linewidth should therefore not be treated as the sole performance metric.

Perovskites exhibit excellent absorption and emission properties but are highly sensitive to heat, moisture, and irradiation. Zhang et al. used femtosecond laser direct nanolithography to control the local hydration of layered perovskites, achieving nanoscale features and pixel-level temporal programmability for programmable holographic optical-field modulation [8]. This work extends ultrafast laser processing from static patterning to time-varying functional control and shows that the processing atmosphere, local compositional changes, and environmental exposure must be

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considered in process design. For transparent electrodes such as ITO, the process must also balance transmittance, sheet resistance, and mechanical integrity [10]. Processing of emerging materials should therefore prioritize stable and repeatable local control while preserving intrinsic material properties, rather than simply pursuing higher pulse energy or smaller linewidths.

4. Current limitations and future directions in ultrafast laser processing

4.1. Major processing challenges

Processing throughput and large-area uniformity directly constrain the scalable application of ultrafast laser processing. Point-by-point or line-by-line scanning fabricates complex structures and validates prototypes. In large-area devices, however, including photovoltaic, display, and flexible thin-film devices, scanning speed and system drift can compromise structural uniformity and increase the manufacturing cost per unit [2].

Another challenge is the complexity of the processing window and its transferability across materials. Materials differ markedly in optical absorption, thermal transport, and defect formation. Even at identical average power, different combinations of pulse duration and scanning strategy can produce distinct nonlinear-absorption and heat-accumulation behavior. Process development still relies heavily on empirical trial and error, and reusable quantitative relationships linking laser parameters to structure, material properties, and device performance remain scarce.

Material damage and interfacial reliability can diminish the performance gains obtained by laser processing. Metals and bulk semiconductors commonly undergo melting, resolidification, and lattice-defect formation, whereas transparent media are susceptible to microcracking and stress-induced birefringence. In 2D materials, excessive thinning or edge oxidation may reduce carrier mobility; perovskites may undergo component volatilization, ion migration, or phase decomposition; and brittle films such as ITO may crack, delaminate, or exhibit increased sheet resistance [7, 8, 10]. Thus, the heat-affected zone of ultrafast lasers does not ensure damage-free processing, and material- and interface-specific damage criteria are required.

Insufficient mechanistic characterization and inconsistent evaluation standards further reduce process predictability and reproducibility. Existing studies often focus on microscopic morphology or a single device metric, without analyzing phenomena from transient energy transfer to long-term lifetime. Moreover, laboratories report fluence, scan overlap, and environmental conditions in different ways, hindering cross-platform comparisons, parameter transfer, and process scale-up [1, 2].

4.2. Development priorities for overcoming key challenges

Beam shaping and parallel processing can improve throughput and large-area uniformity. Spatial light modulation, multifocal parallel processing, and direct laser interference patterning can extend serial scanning to multipoint or area-array processing. Matching such techniques with real-time calibration for system drift and stitching error correction boosts machining efficiency and periodic structure homogeneity.

Because the process window is narrow and the process state is difficult to determine in real time, in situ monitoring and closed-loop control are needed. Time-resolved spectroscopy and in situ imaging can be used to identify ablation thresholds, heat accumulation, and phase-transition states. Pulse energy and scanning parameters can then be adjusted, reducing empirical trial and error and batch-to-batch variation.

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Standardized process-data collection can also improve parameter-screening efficiency and process transferability. Databases should comprehensively record laser parameters, processing environments, structural characterization, device performance, and stability data. Physics-based models or machine-learning methods can then be used to analyze relationships between processing conditions and performance outcomes, supporting multiobjective optimization and cross-platform reproducibility.

In large-scale production, hybrid workflows combining ultrafast laser techniques and traditional micro-nano fabrication outperform laser-only machining schemes. Ultrafast lasers can perform localized modification, 3D writing, and selective removal in conjunction with photolithography, deposition, and packaging, thereby combining the uniformity of conventional processes with the spatial selectivity of laser processing.

Reliability studies and evaluation methods must be improved in parallel. For different materials and device architectures, testing should address damage thresholds, performance changes, and environmental aging; experimental conditions and uncertainty ranges should be clearly reported, and accelerated-aging tests should be used to assess performance retention. The practical industrial value of lab-level performance improvements emerges only when machining results correlate with device service life and stable mass production.

5. Conclusion

Ultrafast laser micro-/nanofabrication combines noncontact processing with 3D selectivity and tailors optical and electrical behavior through surface structuring or localized material modification. Existing studies have demonstrated applications in photodetection, photovoltaics, light-emitting devices, integrated optics, and emerging-material devices. Performance depends on structural morphology and on how processing alters material properties and interfaces.

The engineering adoption of ultrafast laser processing is governed not only by fabrication precision but also by manufacturing efficiency and long-term reliability. Parallel processing and in situ monitoring can improve process stability, standardized data reporting can facilitate parameter transfer and cross-study comparison, and integration with conventional micro-/nanofabrication is better aligned with existing manufacturing infrastructure. In the final analysis, widespread deployment of ultrafast laser techniques in optoelectronic production hinges on optical performance enhancement without severe degradation of electrical properties and device service life.

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