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Recent advances in ultra-precision manufacturing of electronic, photonic and quantum devices

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The continuous miniaturization of electronic systems has driven manufacturing into the ultra-precision regime, where dimensional tolerances fall below 10 nm, and surface quality approaches atomic smoothness. Conventional machining and lithography are inadequate to meet these demands, prompting the evolution of ultra-precision techniques combining deterministic material removal, atomic-scale deposition, and intelligent process control. This review surveys recent advances in mechanical, optical, chemical, and hybrid approaches for fabricating high-performance electronic, photonic, and quantum components with traceable, uncertainty-aware control across length scales. Developments in ultra-precision machining, laser ion beam processing, atomic-layer manufacturing, and additive–subtractive hybrids are highlighted alongside progress in in situ metrology and AI-based feedback control. The integration of explainable AI, digital twins, and adaptive learning is enabling unprecedented autonomy and repeatability in nanoscale production. Future directions emphasize sustainable, data-driven and quantum-level precision manufacturing to meet the requirements of next-generation semiconductors, photonics and quantum electronics. Attaining Precision-at-scale continues to remain a major grand challenge in the sector.

The progressive miniaturization and integration of electronic systems have continuously pushed manufacturing precision toward the atomic scale. Modern electronic components ranging from high-frequency transistors and photonic circuits to quantum sensors require dimensional tolerances below 10 nm, surface roughness within the sub-nanometer range, and material homogeneity. Conventional machining, lithography, and polishing techniques, originally developed for micrometer-scale fabrication, have reached fundamental atomic limits in both spatial control and surface integrity[1,2]. These limitations have catalyzed the emergence of ultra-precision manufacturing (UPM) as a cornerstone technology for next-generation electronic devices[3].

Ultra-precision manufacturing combines deterministic material removal, atomic-scale deposition, and real-time feedback control to achieve form accuracies that approach the limits of lattice spacing[4,5]. Newer directions in the field of nano-fabrication combine mechanical, optical, and chemical techniques complemented by artificial intelligence (AI) and advanced metrology to redefine achievable performance thresholds. The capability to reproducibly manufacture surfaces with atomic smoothness and dimensional fidelity below 10 nm is now central to progress in semiconductors, photonics, flexible electronics, and quantum devices.

The demand for defect-free, high-frequency, and high-power electronic components is the primary driver for innovation in UPM. As feature dimensions shrink and operating frequencies climb into the terahertz regime, slight nanometric deviations in geometry or surface roughness can introduce parasitic losses, interfacial scattering, or unwanted thermal gradients[6,7]. Likewise, in optoelectronic and photonic systems, surface figure accuracy dictates light confinement, mode coupling, and overall device efficiency[8].

Beyond geometry, material microstructure and interfacial quality are emerging as equally critical determinants of performance. The development of deterministic control strategies for subsurface damage, grain orientation and residual stress has become integral to achieving reliable device performance at the nanoscale[9]. Meanwhile, cross-pollination between semiconductor fabrication, optics and quantum engineering has introduced new hybrid demands such as the co-fabrication of superconducting, dielectric and metallic layers on ultra-flat substrates.

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Environmental stability, digital process orchestration, and data-informed modeling are now indispensable. Cleanroom-grade control of temperature, vibration, and humidity must be coupled with digital twins and AI-driven optimization to maintain precision during long machining cycles[10]. Such developments underscore a paradigm shift: from empirically tuned processes toward model-based, adaptive, and autonomous ultra-precision manufacturing.

This review aims to present a comprehensive and critical synthesis of the recent advances in ultra-precision manufacturing (UPM) of high-performance electronic components. The focus extends across mechanical, optical, chemical, and hybrid approaches that define the state-of-the-art in sub-micrometer material processing. In doing so, we examined how deterministic mechanics, laser-ion beam interactions, atomic-layer fabrication, and additive–subtractive hybrids are transforming the production of functional electronic architectures.

The review also emphasizes the integration of advanced metrology, machine learning, and explainable AI as enablers of reproducible, data-driven manufacturing. Finally, emerging trajectories such as sustainable process design, autonomous control frameworks, and quantum-level precision are discussed to chart the path toward next-generation production systems. Through this synthesis, we aim to provide researchers and practitioners with a cohesive understanding of how UPM principles are being redefined by interdisciplinary innovation and digital intelligence. Although the fabrication processes reviewed in this paper are governed by fundamentally different physical mechanisms, mechanical, photonic, ionic, chemical, and hybrid, they should not be interpreted as isolated or mutually exclusive alternatives. Instead, they form a hierarchical and complementary manufacturing ecosystem, in which different process classes address different length scales, material responses, and functional requirements. In modern ultra-precision manufacturing, mechanical processes typically establish global geometry, beam-based processes provide localized nanometric correction, atomic-layer techniques finalize interfaces and functional layers, and additive-hybrid approaches enable complex 3D architectures. The relationships among these processes are therefore best understood not as purely competing, but as strategically orchestrated within multi-stage process chains, with competition arising only in specific, well-defined use cases. This review is structured around this systems-level view of manufacturing, emphasizing not only individual process capabilities, but also how different physical mechanisms interact, complement, or substitute each other in practical manufacturing workflows.

It is also important to note that, in ultra-precision manufacturing, reported nanometric or sub-nanometric capabilities must be interpreted within the framework of precision engineering. Ultimate performance is governed not only by process resolution, but by traceable metrology, uncertainty budget, and deterministic control of error sources across the entire manufacturing value chain. As feature sizes approach atomic dimensions, the distinction between local resolution and global accuracy becomes increasingly critical, particularly for scalable and industrially relevant production.

Evolution of ultra-precision manufacturing in electronics

Historical context

The origins of ultra-precision manufacturing (UPM) trace back to optical fabrication and single-point diamond turning (SPDT) in the mid-twentieth century, when researchers sought methods to produce diffraction-limited optical surfaces for infrared systems[11] Early breakthroughs, such as the development of air-bearing spindles, hydrostatic slides, and diamond-tipped cutting tools, enabled machining with form accuracy below 1 μm and surface roughness below 10 nm[12,13]. These innovations marked the transition from artisanal polishing to deterministic machining, establishing UPM as a distinct scientific discipline grounded in process modeling and precision metrology (Fig. 1).

The need for miniaturization put a constraint on the size of electronic components that shifted the focus of UPM from optics to semiconductor substrates. Ion-beam figuring (IBF) and magnetorheological finishing (MRF) offered atomic-scale material removal through momentum-controlled particle or ion bombardment[14,15]. Meanwhile, chemo–mechanical polishing (CMP) evolved from planarization of optical wafers to integrated-circuit interconnect fabrication, achieving uniformity within tens of nanometers[16]. Together, these milestones laid the foundation for the nanometric precision now demanded by modern microelectronics and photonics.

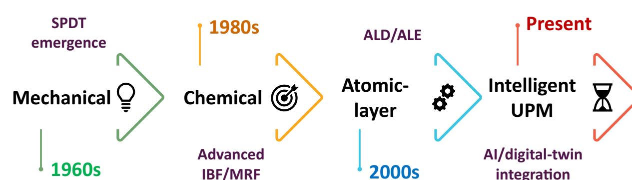

Fig. 1 | Evolution of ultra-precision manufacturing (UPM) over the past few years.

Transition to digital and data-centric precision

The late twentieth century witnessed a decisive digital transformation in UPM. The introduction of computer numerical control (CNC) architecture provided deterministic servo motion with nanometer-scale interpolation. Environmental isolation through active vibration damping and thermal stabilization reduced the drift to below 10 nm over extended machining cycles[17]. However, these advances alone could not ensure repeatability at the atomic level; they required integration with high-fidelity sensors and model-based compensation.

This period also marked the convergence of precision metrology and computational modeling. Surface-error maps derived from interferometric measurements began to feed directly into tool-path correction algorithms, enabling “error-feedforward” machining[18]. Process optimization transitioned from empirical parameter sweeps to predictive modeling grounded in contact mechanics, thermomechanics, and fluid dynamics[19]. The concept of deterministic fabrication, where each stage of machining, polishing, and cleaning is guided by quantitative feedback, became a defining characteristic of next-generation manufacturing systems.

The digital revolution further accelerated with the advent of cyber-physical systems and high-speed data acquisition. Machine learning (ML) algorithms began to predict tool wear, surface morphology, and vibration signatures, allowing proactive compensation[20]. These capabilities transformed UPM from an operator-driven process to a data-centric manufacturing ecosystem, where intelligent control systems continuously refine machining accuracy in real time[21].

Current capabilities and remaining barriers

Modern ultra-precision platforms now routinely achieve form accuracies below 50 nm and surface finishes below 1 nm Ra on metals, ceramics, and semiconductor wafers. Advanced diamond-turning machines can maintain spindle errors below 0.05 μm, while ion-beam and plasma-etching tools provide sub-nanometer material removal per pass. Real-time interferometry, atomic-force microscopy (AFM), and X-ray topography enable measurement and correction of nanometric deviations during processing. Such capabilities have unlocked widespread industrial adoption in semiconductor wafer planarization, photonic component shaping, and MEMS packaging[17,22,23].

Yet, formidable challenges persist. Tool wear and degradation remain major sources of uncertainty, particularly when machining hard or brittle materials such as SiC, GaAs, GaN, and sapphire[24]. The multi-physics coupling among cutting force, thermal expansion, and surface chemistry complicates predictive modeling across scales. Moreover, as tolerances shrink below the grain size of the material, stochastic effects, atomic dislocations, amorphous phases, or adsorbed contaminants begin to dominate process variability[25]. These nanoscale phenomena cannot yet be fully captured by conventional continuum mechanics or empirical control strategies.

Another enduring obstacle is scalability. Processes that deliver atomic-level accuracy for small optical lenses or test coupons often struggle to

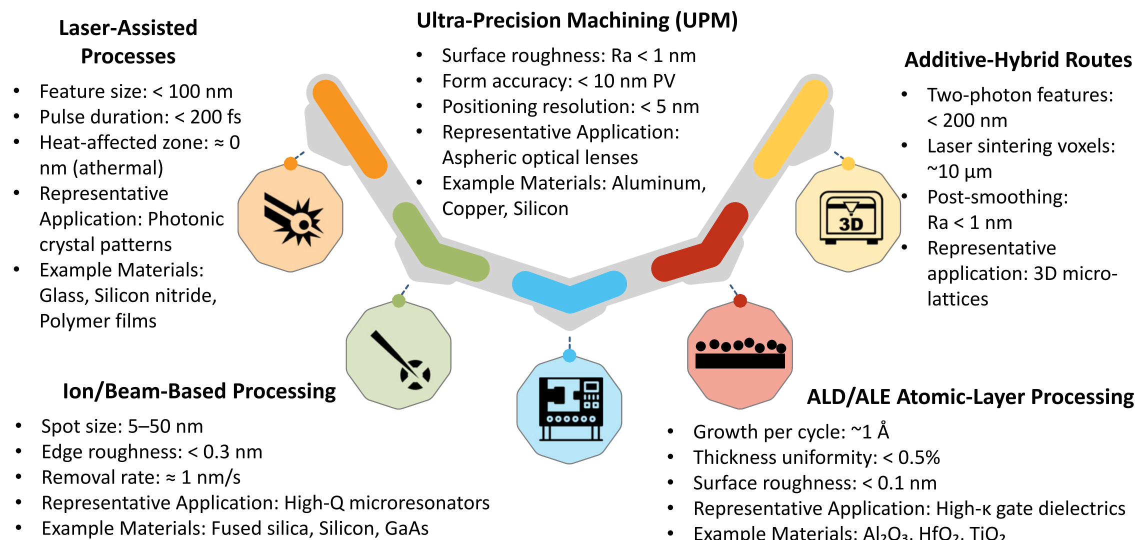

Fig. 2 | Comparison of major UPM techniques.

maintain uniformity over wafer-scale or roll-to-roll substrates[26]. Throughput and cost constraints also limit widespread industrialization. Addressing these barriers requires not only improved tool materials and environmental control but also the integration of AI-driven feedback loops and digital-twin simulations to bridge the gap between laboratory precision and mass-production reliability.

Ultra-precision fabrication techniques

This section presents a detailed overview of the core fabrication strategies that define modern ultra-precision manufacturing (UPM) for electronic, photonic, quantum, and advanced packaging components. These methods collectively enable deterministic control, of material structure, geometry, and surface integrity at sub-nanometer scales as shown in Table S1. These methods collectively enable deterministic control of material structure, geometry, and surface integrity at sub-nanometer scales[27]. Ultra-precision machining (UPM) serves as the foundational approach, utilizing single-point diamond turning, ultra-fine grinding, and magnetorheological polishing to achieve mirror-grade finishes and dimensional fidelity below 10 nm on metals, semiconductors, and ceramics. Laser and beam-assisted processes extend this precision through non-contact energy delivery, where femtosecond laser ablation, focused ion beam trimming, and hybrid laser-assisted machining facilitate nanometric feature definition even in hard or brittle materials, as shown in Fig. 2. Chemical and atomic-layer fabrication techniques, including atomic layer deposition (ALD) and atomic layer etching (ALE), introduce molecular-scale control by leveraging self-limiting surface reactions to deposit or remove materials one atomic layer at a time[28].

These processes underpin the creation of high-κ dielectrics, barrier films, and heterostructures critical for sub-10 nm semiconductor devices. Finally, additive and hybrid UPM methods integrate nanoscale additive manufacturing, such as two-photon polymerization and micro-laser sintering, with deterministic subtractive finishing and in situ metrology. This integration enables the fabrication of complex 3D micro-architectures with accuracies approaching 100 nm and surface roughness below 10 nm. Together, these complementary techniques demonstrate how mechanical precision, photonic energy control, chemical self-assembly, and digital feedback converge to realize next-generation electronic, photonic, and quantum components with atomic-level reproducibility[28].

Ultra-precision machining (UPM)

Ultra-precision machining (UPM) represents the foundation of deterministic fabrication for electronic and photonic components, where surface integrity and dimensional fidelity below the 10 nm scale are required. The process encompasses single-point diamond turning (SPDT), ultra-fine grinding, and fluid-jet or magnetorheological polishing, all designed to achieve atomically smooth surfaces on metals, semiconductors, and ceramics[20,29–31]. From a comparative perspective, ultra-precision machining offers unmatched form accuracy, surface integrity, and industrial maturity, making it highly suitable for large-area optics, molds, and precision mechanical and packaging components. However, its limitations include relatively low material-removal rates, tool wear, and restricted applicability to extremely hard or chemically sensitive materials. While UPM is scalable and robust in industrial environments, its throughput and cost efficiency become limiting when atomic-layer control or complex 3D nanoscale features are required, motivating the use of beam-based or chemical techniques in such cases[32].

Process principles and deterministic control

UPM allows machining of brittle and hard materials in the so-called "ductile-mode" where chip formation occurs through plastic flow rather than brittle fracture, leaving behind an optically smooth machined surface. Maintaining consistency of ductile-mode machining demands precise coordination of tool geometry, feed rate, cutting depth, and spindle speed[33]. The deterministic nature of UPM stems from its reliance on nanometric feedback loops, position sensors with sub-nanometer resolution, interferometric spindle encoders, and temperature-compensated linear drives. These systems collectively suppress tool-path errors, chatter, and thermal drift during long-duration cycles[34].

Advanced UPM machines are equipped with multi-axis hydrostatic or aerostatic bearings that minimize friction and vibration, achieving spindle motion errors below 0.05 µm. Process performance is further enhanced by error-mapping calibration, wherein geometric deviations of each axis are characterized through laser interferometry and compensated in real-time by closed-loop servo control[35,36]. Such deterministic error correction allows continuous machining of optical-grade surfaces with sub-10 nm form error (see Fig. 3).

Materials and surface integrity

Recent research has expanded UPM applicability beyond traditional materials such as aluminum and copper to hard and brittle substrates silicon, GaAs, fused silica, and silicon carbide[33]. Achieving ductile cutting in these materials requires optimization of undeformed chip thickness and lubrication conditions to suppress micro-cracking. Nanometric surface finishes (<1 nm Ra) have been reported using

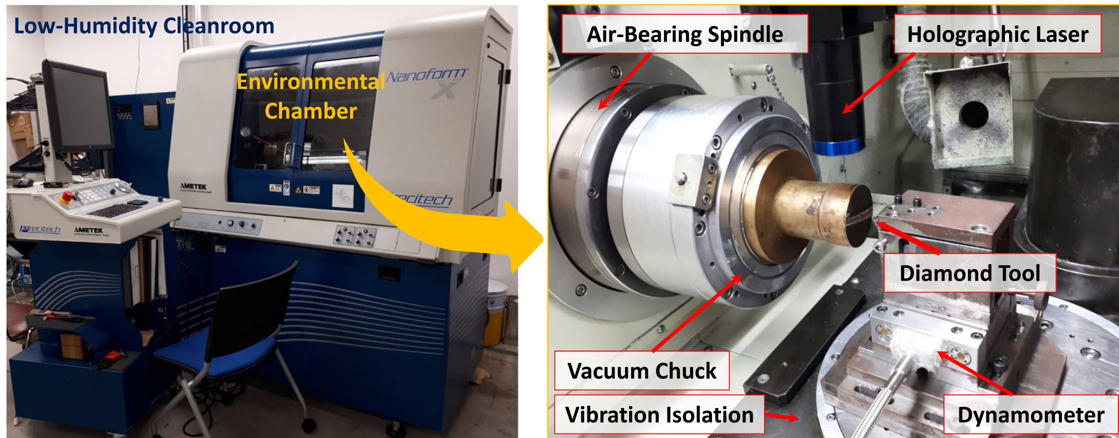

Fig. 3 | Architecture of a single-point diamond turning machine.

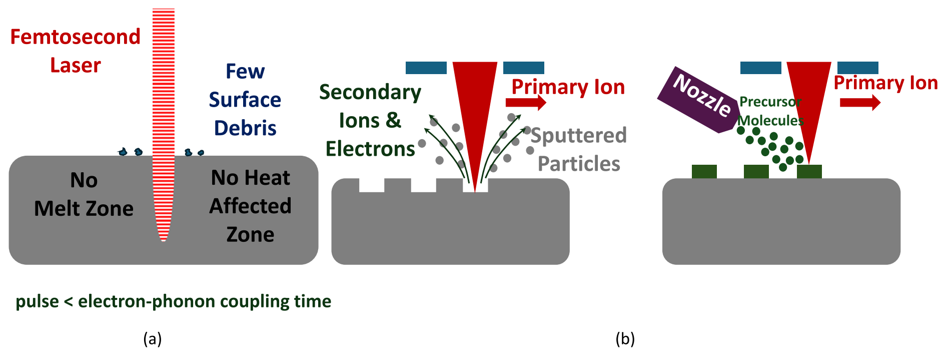

Fig. 4 | Laser and ion-beam interaction with matter during manufacturing. Schematic illustration showing the mechanism of **a** ultrafast laser and **b** ion-beam nanofabrication.

cryogenic or ultrasonic-assisted diamond turning, which lowers cutting temperature and mitigates tool wear[37].

Subsurface integrity is equally critical. Transmission electron microscopy (TEM) studies reveal that controlling tool workpiece interaction energy can limit dislocation density and amorphous layer formation to within a few nanometers[38]. This control is particularly vital for micro-optoelectronic housings and waveguide substrates, where buried defects degrade optical transmission or induce localized thermal stresses[39].

Applications in electronics and photonics

UPM underpins the production of MEMS housings, microlens arrays, high-frequency interconnects, and optical cavities. In semiconductor packaging, UPM enables cavity sealing and surface planarization with minimal residual stress. In photonics, it is employed to shape freeform mirrors and diffraction-limited resonators used in laser cavities and LiDAR systems[29]. The combination of deterministic error mapping, environmental isolation, and real-time compensation has allowed commercial machines to achieve sub-nanometer surface roughness on optical and metallic components exceeding 200 mm in diameter[40].

Ongoing research focuses on integrating in situ metrology, for instance, white-light interferometry and optical coherence tomography, directly within the machining environment, thereby enabling dynamic feedback and process self-correction[41]. Such integration marks the transition of UPM from a high-precision but sequential process to an intelligent, adaptive manufacturing platform capable of sustained sub-nanometer reproducibility[42].

Laser- and beam-assisted techniques

The emergence of laser and charged particle-based processing has revolutionized ultra-precision fabrication by enabling non-contact, localized energy delivery with spatial resolution approaching a few nanometers. These approaches overcome many of the material limitations inherent to mechanical cutting and grinding, particularly for hard or brittle substrates such as SiC, GaN, sapphire, and fused silica[43]. Compared to mechanical UPM, laser and beam-based techniques provide superior flexibility, non-contact processing, and access to extremely hard, brittle, or functional materials. They excel in localized nanostructuring, trimming, and repair, but are constrained by limited throughput, high equipment cost, and challenges in large-area uniformity. In addition, beam-induced damage, redeposition, and thermal effects require careful mitigation, making these methods more suitable for high-value, low-volume manufacturing, prototyping, and device-level correction rather than high-throughput production[44].

Ultrafast laser micromachining

Ultrafast (femtosecond to picosecond) lasers achieve deterministic material removal through non-thermal ablation, where the pulse duration is shorter than electron-phonon coupling times. This confines energy to the focal volume, minimizing collateral heat-affected zones (HAZ)[36]. Pulse-shaping and beam-scanning strategies, spatiotemporal focusing, burst-mode modulation, and helical trepanning enable surface roughness below 10 nm and edge taper less than 1°[45,46].

In semiconductor processing, ultrafast lasers are now used for drilling, transparent-electrode patterning, and wafer-dicing without microcrack propagation[38]. In photonics, they facilitate the direct inscription of waveguides, Bragg gratings, and resonant microcavities inside glass or crystalline substrates with sub-micrometer positional accuracy[45]. The deterministic control of ablation threshold via real-time fluence monitoring has made femtosecond laser machining (Fig. 4a) a cornerstone of high-value micro-optical fabrication involving the removal of atoms through a complex electron and photon interaction (Fig. 4b).

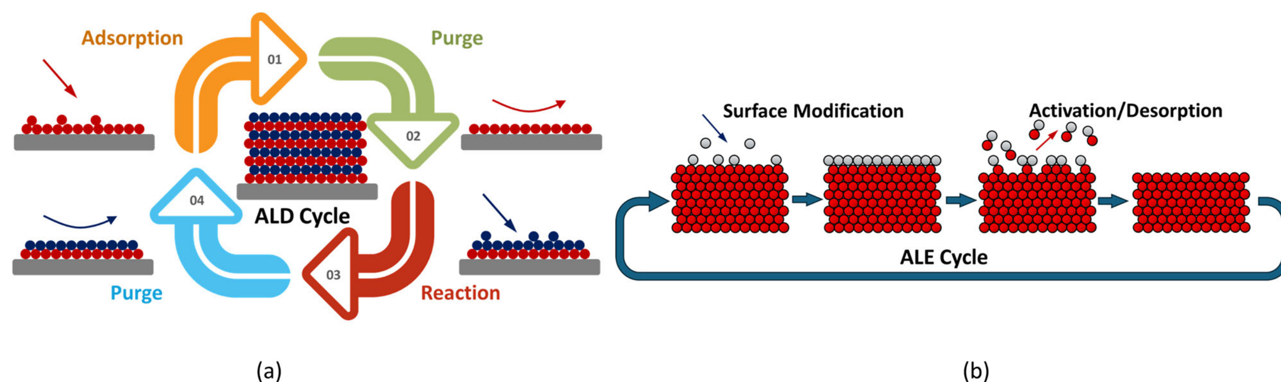

Fig. 5 | Comparison of controlled atomic-scale growth and removal. Schematic illustration revealing the principle of **a** atomic layer deposition (ALD) and **b** atomic layer etching (ALE) processes.

Focused ion and electron beam processing

Focused ion beam (FIB) and electron beam (EB) techniques extend precision fabrication into the atomic regime through controlled sputtering, implantation, or deposition. In FIB trimming, gallium or helium ions selectively remove or modify surface layers at rates of a few atoms per pulse, allowing nanometric correction of device features such as photonic crystal cavities or microresonator couplers[40]. Meanwhile, EB-induced deposition and milling provide versatile routes for repairing interconnects and forming nanoscale electrodes directly on device wafers[47,48].

Recent developments in multi-beam ion sources and gas-assisted etching have enhanced throughput while retaining atomic precision[49]. Combining these processes with cryogenic stage control suppresses beam-induced damage and re-deposition, extending applicability to sensitive materials including III–V semiconductors and 2D materials[47]. The incorporation of in situ electron backscatter diffraction (EBSD) and secondary-ion mass spectrometry (SIMS) now allows closed-loop correction based on crystallographic or compositional feedback[50].

Hybrid laser-assisted machining

Laser-assisted machining (LAM) synergistically integrates focused laser heating with mechanical removal to soften the cutting zone, reducing tool wear and cutting forces[51]. By pre-heating a narrow region ahead of the tool, LAM transitions brittle substrates into a ductile regime, enabling mirror-finish surfaces on SiC or GaN. Advanced LAM platforms combine temperature feedback with adaptive control of laser power and tool feed, maintaining uniform material removal within ±5 nm[52]. Some aspects of the implementation of micro-LAM should exercise caution, as discussed recently[53].

Hybrid laser-ion beam systems further expand capability through sequential energy delivery, i.e., laser pre-conditioning modifies surface stress or oxide layers, followed by deterministic ion-beam smoothing[54]. This dual-mode approach achieves form accuracies below 10 nm over millimeter-scale apertures, useful for photonic mirrors and superconducting circuit substrates.

Chemical and atomic-layer fabrication

Chemical and atomic-layer fabrication methods extend the reach of ultra-precision manufacturing into atomic and molecular domains, where material growth and removal are governed by self-limiting surface reactions rather than mechanical or energetic impacts. Methods such as atomic layer deposition (ALD) and atomic layer etching (ALE) offer unrivaled control of film thickness, uniformity, and composition at the angstrom scale[55,56]. When integrated with in situ diagnostics and adaptive control, they enable reproducible fabrication of defect-free layers crucial for advanced electronic, optoelectronic, and quantum devices. Atomic-layer techniques offer unparalleled control over thickness, composition, and interface quality, making them indispensable for advanced semiconductor, photonic, and quantum devices[55,57]. Their principal limitations lie in low deposition or etch rates, high process complexity, and cost-intensive equipment infrastructure. Consequently, while ALD and ALE are irreplaceable for atomic-scale interface engineering, they are typically combined with faster, less precise processes to achieve acceptable throughput and economic viability at the system level[58].

Atomic layer deposition (ALD)

ALD is a cyclic, self-limiting process where gaseous precursors sequentially react with a substrate surface, forming one atomic layer per cycle. Each cycle typically involves alternating exposures of precursor A (adsorption) and precursor B (reaction), separated by inert gas purges. This sequence ensures that surface saturation, not reaction kinetics, dictates the deposition rate, yielding sub-angstrom thickness precision and conformality over complex 3D geometries[59,60].

In semiconductor manufacturing, ALD has become indispensable for high-κ dielectrics (HfO_2, Al_2O_3), barrier layers, and gate oxides in sub-10 nm transistors[49]. Its low-temperature variants (plasma-enhanced ALD, spatial ALD) allow coating of thermally fragile materials such as polymers and 2D semiconductors, facilitating integration in flexible and heterogeneous electronics[61]. Moreover, ALD-grown films often exhibit superior density and interface sharpness compared with physical vapor deposition (PVD), significantly reducing leakage and diffusion defects[62].

Recent developments in area-selective ALD (AS-ALD) enable spatially patterned deposition without lithography by exploiting surface-chemistry contrasts or localized inhibitors. Combined with in situ metrology such as spectroscopic ellipsometry or quartz-crystal microbalance (QCM), AS-ALD allows real-time monitoring of growth per cycle, ensuring deterministic film formation with sub-nanometer accuracy (Fig. 5a)[63].

Atomic layer etching (ALE)

Complementary to ALD, atomic layer etching (ALE) achieves atomically precise material removal through sequential, self-limiting surface modification and desorption steps. Typically, an adsorption phase (e.g., halogenation or oxidation) modifies the upper atomic layer, followed by a low-energy ion or thermal activation that removes the modified species[64]. This approach decouples selectivity and anisotropy from stochastic ion bombardment, eliminating subsurface damage common in reactive ion etching (RIE).

ALE has demonstrated angstrom-scale etch control in materials such as Al_2O_3, SiO_2, and III–V semiconductors, enabling precise pattern transfer for advanced logic and memory devices[65]. When combined with time-resolved plasma control or ion energy modulation, ALE can achieve smooth, damage-free surfaces suitable for high-performance photonic or quantum circuits. Emerging hybrid schemes, alternate ALE and ALD cycles, are proposed to build superlattice structures or interface-engineered heterostructures with atomic-level fidelity (Fig. 5b)[55].

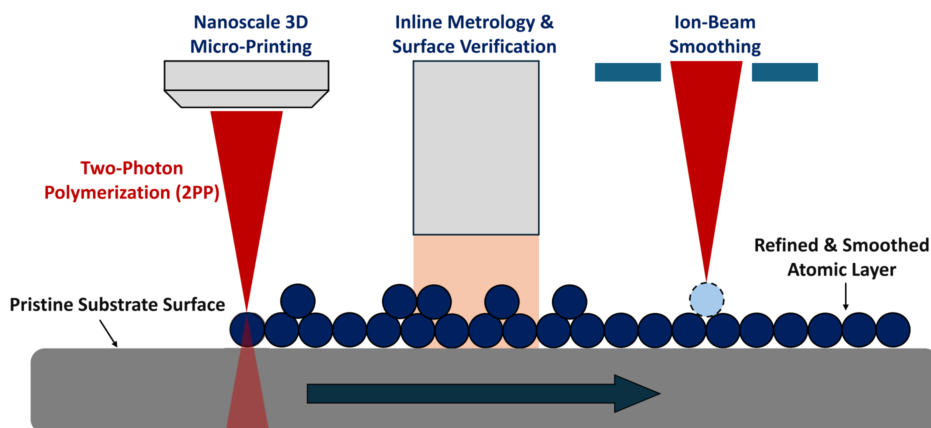

Fig. 6 | Hybrid additive–subtractive UPM workflow.

Integration and hybridization

The frontier of atomic-layer manufacturing lies in process integration coupling, ALD/ALE with in situ metrology, data-driven models, and hybrid additive–subtractive workflows. For example, combining ALD with focused ion beam (FIB) trimming allows local deposition of functional nanostructures, while integrating ALE into wafer-scale CMP workflows offers precise surface correction without mechanical contact[55,66].

Furthermore, chemical precision is increasingly coupled with digital intelligence: machine learning algorithms now predict precursor adsorption kinetics and surface reaction pathways, optimizing process conditions dynamically[67]. This data-centric control paradigm moves atomic-layer fabrication from empirical tuning toward self-optimizing, reproducible nanoscale production.

Additive and hybrid ultra-precision manufacturing

Additive and hybrid ultra-precision manufacturing approaches represent the convergence of material accretion and controlled subtraction, enabling complex three-dimensional architectures with atomic-to-mesoscale accuracy. Unlike conventional additive manufacturing (AM), which prioritizes geometric freedom, these techniques emphasize dimensional determinism, surface integrity, and functional integration at the micro- and nanoscale[68]. By merging additive methods such as two-photon polymerization or micro-laser sintering with ultra-precision finishing and in situ metrology, hybrid systems achieve component accuracies unattainable through either paradigm alone (Fig. 6). Additive and hybrid ultra-precision approaches offer unique advantages in geometric complexity and functional integration but currently face challenges in process stability, material quality, and industrial robustness. While they provide unprecedented design freedom and enable integrated fabrication-finishing workflows, their throughput, reliability, and long-term repeatability generally lag behind more established subtractive or planar processing routes, limiting their present adoption mainly to specialized, high-value applications[69].

Nano-scale additive manufacturing

Advances in high-resolution additive fabrication particularly two-photon polymerization (TPP) and micro-laser sintering (MLS) have extended print resolution into the sub 100 nm regime. In TPP, femtosecond laser pulses induce localized polymerization only at the focal point where photon density surpasses a nonlinear absorption threshold[70]. This permits three-dimensional freeform structuring with voxel dimensions of ~100 nm and surface roughness <10 nm after post-curing. Functionalized resins incorporating conductive nanoparticles, photopolymers, or dielectric fillers enable direct fabrication of micro-optical, microfluidic, and electronic interconnect structures[71].

Micro-laser sintering, by contrast, selectively melts or bonds fine metallic or ceramic powders under laser irradiation. Its ability to generate dense, crack-free microstructures has made it particularly valuable for MEMS packaging, micro-heat exchangers, and RF interconnects[72]. However, challenges in powder uniformity, oxidation, and layer thickness control persist. To overcome these, hybrid systems integrate in situ monitoring (e.g., high-speed pyrometry and optical coherence tomography) with closed-loop correction algorithms, achieving reproducibility across multiple build cycles[73].

Additive–subtractive hybrid workflows

Hybrid ultra-precision systems combine additive deposition with deterministic subtractive finishing within a single machine environment. For example, a metallic or a polymeric microstructure can be additively built and subsequently polished or machined using diamond tools or focused ion beams to reach sub-nanometer surface finishes. This closed-loop integration eliminates misalignment between stages and compensates for thermal distortion or residual stresses induced during additive steps[74].

One emerging strategy employs laser-assisted additive deposition followed by ion-beam smoothing to achieve mirror-grade optical surfaces directly after printing[75]. Similarly, hybrid micro-turning combined with electrochemical polishing has been applied to achieve sub-50 nm roughness on microshafts and precision connectors[76]. These integrated workflows significantly shorten processing chains while ensuring dimensional traceability across fabrication stages.

In situ monitoring and closed-loop correction

The success of additive-hybrid UPM depends heavily on real-time process monitoring. Embedded sensors measuring temperature, acoustic emissions, and optical reflectance provide data for adaptive feedback control[77]. Machine learning models trained on multi-sensor datasets predict layer thickness, defect occurrence, and melt-pool dynamics, allowing the system to autonomously adjust laser power, feed rate, or beam focus in response to deviations[78].

Digital twins virtual process replicas updated in real-time are increasingly used to simulate heat transfer, stress accumulation, and solidification behavior, enabling predictive corrections before defects manifest physically[79]. The integration of such models with high-bandwidth control systems moves additive manufacturing toward self-stabilizing ultra-precision fabrication, where dimensional deviations remain below 100 nm even in complex geometries[80].

Cross-comparison and process selection trade-offs

A critical consideration from a precision engineering standpoint is the distinction between global form control and localized error correction. Although all ultra-precision manufacturing techniques aim at nanometric or atomic-scale control, they differ fundamentally in achievable precision, throughput, scalability, cost, and robustness. Mechanical UPM provides the best combination of large-area scalability, robustness, and surface integrity, but is limited in minimum feature size and tooling choices. Beam-based techniques offer superior spatial resolution and material versatility, at the expense of throughput and capital cost. They are also inherently limited in

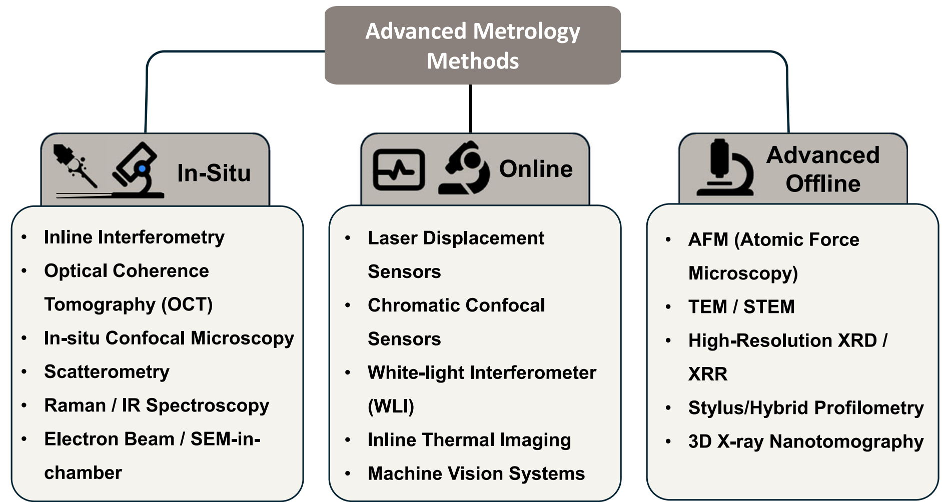

Fig. 7 | Multi-modal metrology and in situ monitoring framework.

throughput and are not designed to establish large-area form accuracy. Atomic-layer processes deliver unmatched interface and thickness control but suffer from intrinsically slow processing rates. Additive and hybrid approaches maximize design freedom but remain comparatively immature in terms of reproducibility and industrial readiness[81,82].

In practice, no single technique dominates across all performance metrics. Instead, modern manufacturing chains increasingly rely on hierarchical process integration, in which high-throughput methods establish geometry, ultra-precision processes refine form and surfaces, and atomic-layer techniques finalize interfaces and functional layers. The optimal process route is therefore dictated not only by target precision, but also by economic constraints, production volume, material system, and system-level performance requirements[83].

Hierarchical integration, complementarity, and process competition

Although ultra-precision manufacturing processes are often compared in terms of their ultimate resolution or achievable surface quality, their most important distinctions lie in their functional roles within the manufacturing chain. Mechanical processes dominate large-area form generation and bulk material removal; beam-based methods provide localized, high-resolution correction and structuring; atomic-layer techniques deliver atomic-scale interface and thickness control; and additive-hybrid approaches integrate geometry creation with finishing in a unified workflow[84,85]. In practice, these methods are therefore primarily complementary rather than competing. True competition arises only in specific process windows, for example, between ion-beam figuring and ultra-precision polishing for surface correction, or between ALE and gentle plasma etching for interface preparation. Even then, the choice is dictated by material system, damage tolerance, scale, and economic constraints rather than by resolution alone[81].

Modern manufacturing routes increasingly adopt a hierarchical, multi-stage architecture, in which different physical mechanisms are orchestrated across length scales from millimeters down to angstroms to achieve both efficiency and ultimate precision. This systems-level perspective is essential to understand how ultra-precision manufacturing operates in the industrial landscape[86].

Advanced metrology and in situ monitoring

Metrology underpins the credibility and reproducibility of ultra-precision manufacturing (UPM). As fabrication tolerances approach the atomic scale, metrology evolves from a post-process verification tool into an integrated, active element of the manufacturing system. Contemporary advances in high-resolution instrumentation, sensor fusion, and data analytics now allow measurement precision below 1 nm, even under industrial conditions. The interplay between deterministic fabrication and intelligent metrology has become central to achieving both accuracy and scalability in nanoscale component production (Fig. 7).

High-resolution metrology

High-resolution metrology in UPM relies on optical interferometry, scanning probe techniques, and X-ray-based diagnostics, each offering unique trade-offs between spatial resolution, measurement bandwidth, and environmental robustness.

Optical interferometry

Including white-light, phase-shifting, and coherence scanning variants remains the workhorse for non-contact surface profiling with sub-nanometer vertical resolution. Modern interferometers integrated with vibration-isolated stages and temperature-controlled enclosures can maintain repeatability better than 0.2 nm over centimeter-scale fields of view[87,88]. Advanced signal-processing methods such as phase-unwrapping algorithms and adaptive filtering mitigate noise from air turbulence or surface reflectivity variations, enabling reliable measurement of optical-grade surfaces[89].

Scanning probe methods, such as atomic force microscopy (AFM) and scanning tunneling microscopy (STM), extend metrological capability into the atomic regime[90]. These instruments capture nanoscale morphology, step height, and surface energy distributions with vertical resolution approaching 0.1 nm. However, their limited scan area and slow throughput necessitate hybrid metrology strategies that combine AFM for local calibration with interferometry for global mapping[91].

For crystalline and buried structures, X-ray computed tomography and X-ray reflectometry provide nondestructive insight into lattice strain, dislocation density, and interface roughness[92]. The use of synchrotron-based coherent X-ray imaging and ENGIN-X-based neutron diffraction has recently achieved picometer-scale displacement sensitivity, facilitating correlation between process parameters and atomic lattice distortions[93]. New sensors are being developed by realizing the potential of new materials[94].

In situ monitoring systems

Traditional UPM workflows relied on offline inspection between machining or polishing steps. Modern manufacturing now embeds real-time in situ monitoring systems directly within the machine tools, combining optical, acoustic, and thermal sensors to provide continuous feedback on tool–workpiece interactions[95].

Optical sensors, including confocal microscopy and digital holography, capture surface evolution during cutting or deposition without interrupting the process. Acoustic emission sensors detect micro-fracture, chatter, and tool wear at frequencies exceeding 1 MHz, offering early warning of subsurface damage[74]. Infrared and

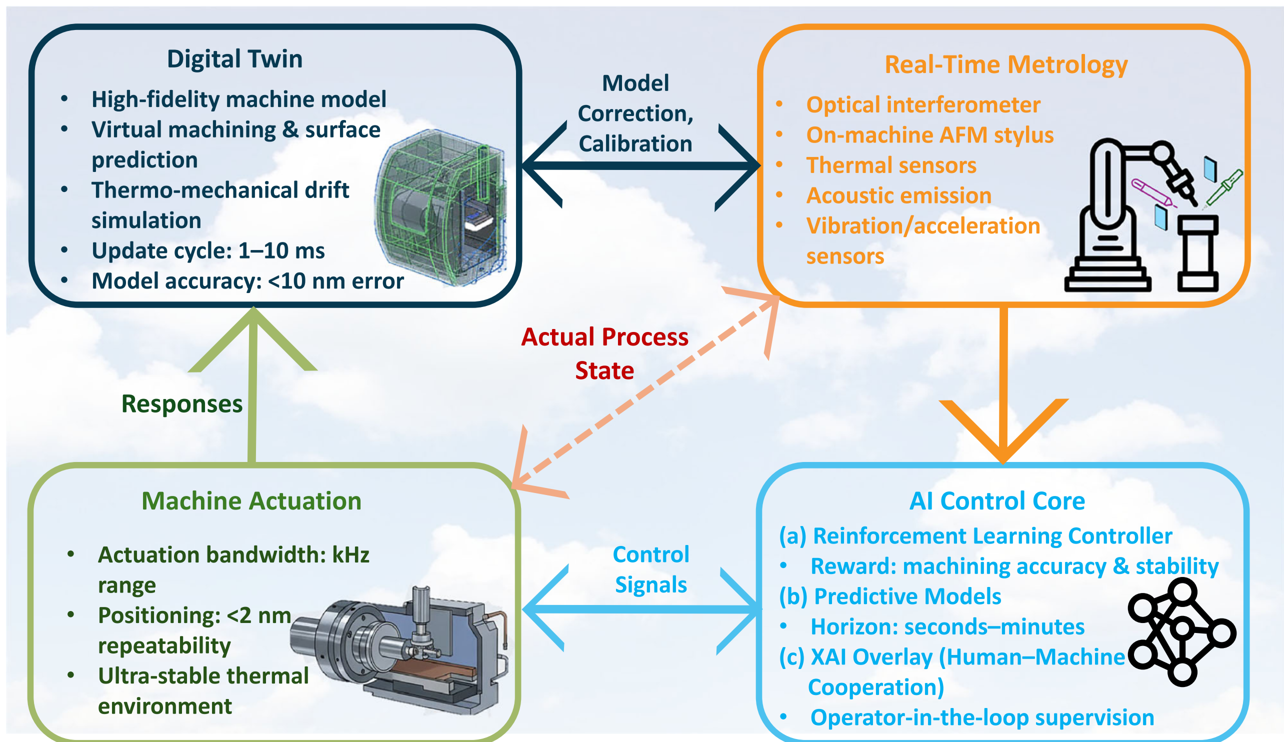

Fig. 8 | AI-driven autonomous UPM ecosystem.

thermoreflectance sensors measure transient thermal fields, enabling compensation for expansion-induced form errors in real time[96].

Emerging machine tools integrate these multi-sensor data streams through edge computing platforms, where lightweight AI algorithms perform on-machine analytics. This architecture allows immediate adaptive correction, such as adjusting tool feed, spindle speed, or coolant flow, to maintain sub-micrometer stability over prolonged cycles[72]. In advanced laser or ion-beam systems, in situ monitoring has progressed to include plasma emission spectroscopy and time-resolved scattering diagnostics, providing atomic-scale insight into ablation or deposition dynamics[72].

Data fusion and real-time control

The true power of modern metrology lies not only in measurement precision but in data fusion and intelligent interpretation. Multi-modal sensing combining optical, mechanical, and thermal data enables comprehensive state awareness of the fabrication process. Integrating these streams through machine learning and model-based algorithms transforms raw data into actionable control signals[72,97].

Digital holography and optical coherence tomography (OCT) can reconstruct surface profiles in real time, feeding error maps directly into CNC control loops[98]. Data-driven fusion models correlate sensor signatures with process variables such as tool wear, cutting forces, or beam stability, predicting deviations before they manifest as defects. Reinforcement-learning-based controllers can autonomously tune machining parameters, balancing precision and throughput dynamically[99].

At the systems level, *metrology-driven digital twins* synchronize virtual and physical manufacturing states. These twins continuously ingest in situ measurements to refine process simulations, enabling predictive adjustments that pre-empt drift or tool degradation. Such real-time adaptive metrology transforms UPM into a self-correcting ecosystem where measurement, analysis, and actuation coexist within a unified digital framework[79,100].

Data-driven and AI-augmented ultra-precision manufacturing

The convergence of artificial intelligence (AI), machine learning (ML), and cyber-physical systems is reshaping ultra-precision manufacturing (UPM) from an empirically tuned practice into an adaptive, autonomous science. As tolerances shrink below the nanometer scale, traditional model-based process control becomes insufficient to handle complex, nonlinear interactions among mechanical, thermal, and chemical domains. AI provides a scalable framework to interpret high-dimensional sensor data, predict system behavior, and optimize fabrication in real time. This section reviews (Fig. 8 and Table S2) the evolution of data-driven intelligence in UPM, highlighting recent progress in process optimization, explainable AI, digital twins, and autonomous control frameworks.

Machine learning for process optimization

Machine learning has emerged as a transformative tool for predicting tool wear, optimizing surface morphology, and mitigating thermal drift in the UPM environment. In deterministic machining, regression-based models and neural networks can forecast cutting-force evolution, enabling dynamic compensation before precision loss occurs[101].

In optical polishing and grinding, Gaussian process regression (GPR) and support vector machines (SVMs) have been applied to correlate multi-sensor data such as vibration, temperature, and acoustic emissions with surface quality metrics[102]. This allows process parameters (feed rate, spindle speed, coolant flow) to be optimized dynamically, maintaining consistent surface roughness below 1 nm Ra.

For additive and hybrid UPM, ML algorithms trained on melt-pool imaging and spectral data can predict porosity, layer thickness, and composition uniformity with sub-micron accuracy[103]. Reinforcement learning (RL) frameworks further extend this capability by continuously updating control strategies through trial-based feedback. Such systems have demonstrated autonomous optimization of laser power and scan speed during femtosecond ablation, yielding up to 40% improvement in dimensional fidelity[104].

In recent developments, physics-informed neural networks (PINNs) are bridging data-driven and analytical models, incorporating governing equations of heat transfer, fluid dynamics, and material deformation into ML architectures[105]. This hybrid modeling approach ensures both predictive accuracy and physical interpretability, addressing one of the central challenges in applying AI to precision manufacturing[106].

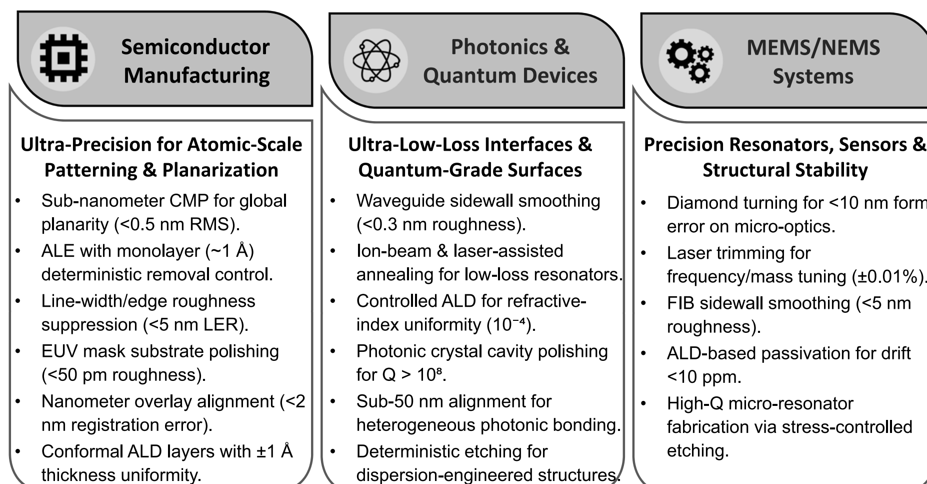

Fig. 9 | Application case studies in semiconductor, photonics & MEMS manufacturing.

Explainable AI and digital twins

While conventional AI offers predictive power, its “black-box” nature limits acceptance in safety-critical manufacturing contexts. Explainable AI (XAI) aims to make decision-making transparent, ensuring that model outputs are interpretable by engineers and can be traced to underlying physical mechanisms[107].

XAI frameworks applied in UPM identify dominant process features influencing surface quality, such as cutting temperature, tool wear progression, or beam stability. By ranking feature importance and visualizing correlations, XAI allows manufacturers to refine process parameters systematically rather than heuristically[108,109]. In semiconductor polishing and thin-film deposition, interpretable ML models have been used to distinguish noise-induced fluctuations from true process drift, improving stability and reproducibility.

Parallel to XAI, digital twin (DT) technology creates a virtual replica of the manufacturing process that evolves synchronously with real-time sensor data. These twins integrate physics-based simulations with data-driven inference, allowing continuous validation and prediction of process outcomes[110]. In ultra-precision machining, DTs simulate spindle dynamics, thermal gradients, and tool deflection at millisecond intervals, enabling pre-emptive correction before deviations accumulate[111].

Advanced digital twins incorporate multi-physics coupling, mechanical, thermal, optical, and chemical phenomena, mirroring the real environment with high fidelity. For instance, in ion-beam figuring or plasma-assisted polishing, DTs predict local removal rates based on plasma density and surface curvature, updating in real time via in situ interferometric feedback[112,113]. This bidirectional coupling between physical and virtual spaces constitutes the foundation of next-generation autonomous manufacturing.

Autonomous control frameworks including responsive manufacturing systems

Autonomy in UPM emerges when sensor feedback, predictive models, and actuation systems are seamlessly integrated into a closed loop. This paradigm moves beyond conventional PID controllers or rule-based control toward cognitive manufacturing, where machines perceive, reason, and act according to the environment[112,113].

Recent frameworks employ deep reinforcement learning (DRL) to achieve real-time control of machining trajectories, beam focus, and environmental parameters. DRL agents learn optimal control policies by maximizing long-term precision metrics, such as minimizing surface deviation or energy consumption[114]. In diamond turning, autonomous compensation systems now detect and correct nanometric thermal drift using ML-based estimators, maintaining sub-10 nm form accuracy over 8-h cycles[115].

Adaptive hybrid controllers combining data-driven inference with model-based prediction have demonstrated resilience against environmental perturbations and material variability[116]. These systems continuously recalibrate their models as soon as new data are registered, thus, effectively “learning” machine dynamics in operation. In hybrid additive–subtractive platforms, adaptive control has achieved nanometric surface uniformity across heterogeneous materials by synchronizing deposition rate and polishing pressure in real time[117].

The integration of edge AI and distributed sensing further decentralizes intelligence, allowing localized decision-making at the machine or tool level. This modular autonomy reduces communication latency and enhances scalability across production networks. When coupled with digital twins and explainable ML, these frameworks represent the foundation of fully autonomous ultra-precision manufacturing ecosystems capable of human-level adaptability and quantum-level repeatability[118,119].

Application domains in electronic, photonic, quantum, and MEMS systems

Although this review is motivated by the need for advanced electronic systems, ultra-precision manufacturing is inherently interdisciplinary and underpins not only electronic devices but also photonic components, quantum hardware, MEMS/NEMS, and heterogeneous integration platforms. In this section, application case studies are therefore discussed across semiconductor electronics, photonics, quantum devices, and precision microsystems, reflecting the true technological reach of modern UPM.

Semiconductor and microelectronics

Semiconductor manufacturing represents the most industrially matured realization of the ultra-precision paradigm, in which atomic-scale control of surfaces, interfaces, and global planarity directly governs device yield, performance, and long-term reliability. Semiconductor and microelectronic fabrication represent the most mature and industrially pervasive applications of UPM, as shown in Fig. 9. The continuous downscaling of transistor dimensions, from the micrometer to sub-5 nm regime, demands manufacturing technologies capable of atomic-level control over planarity, interface integrity, and defect density. As traditional photolithography and chemical–mechanical processing approaches their physical and material limits, ultra-precision methods spanning deterministic polishing, ion-beam figuring and atomic-layer processing have become indispensable to achieving device uniformity and electrical reliability at wafer scale[14,64].

Chemical-mechanical planarization (CMP) and wafer-scale precision

Chemical–mechanical planarization (CMP) remains the industry standard for achieving nanometric global planarity in semiconductor wafers. Modern

CMP integrates nanoparticle-engineered slurries, advanced pad conditioning, and real-time endpoint detection to produce surface flatness below 5 nm across 300 mm wafers[120]. The evolution from conventional alumina-based abrasives to colloidal silica and ceria nanoparticles has enabled smoother finishes and reduced defectivity through enhanced chemical selectivity and lower frictional energy.

Recent efforts focus on deterministic CMP, in which in situ metrology such as optical interferometry, eddy-current monitoring, or motor-torque feedback drives adaptive control of pressure and rotation profiles[121]. By embedding closed-loop feedback within CMP tools, non-uniform removal due to pad wear or slurry depletion is dynamically corrected, yielding reproducibility within ±1 nm across multiple runs.

The combination of CMP with ALD and ALE extends its precision into the angstrom domain. Alternating CMP-ALD cycles are used for ultra-flat dielectric–metal interfaces, crucial for high-k/metal gate transistors and through-silicon vias (TSVs). This hybridization marks the emergence of atomic-level planarization (ALP), a new frontier in wafer-scale fabrication[122].

Sub-10 nm interconnects and defect mitigation

As interconnect line widths shrink below 20 nm, electron scattering, surface roughness, and grain-boundary resistance become dominant performance bottlenecks[123]. Ultra-precision manufacturing addresses these issues by enabling deterministic surface and sidewall engineering through techniques such as ion-beam smoothing, plasma-assisted etching, and self-assembled molecular templating.

In copper and cobalt interconnects, ion-beam-assisted deposition has achieved line-edge roughness below 1 nm, improving electron mobility and reducing electromigration susceptibility[55,75]. Similarly, ALE ensures damage-free trench formation with angstrom-level selectivity, preserving dielectric integrity and reducing leakage currents[124]. Advanced metrology combining X-ray reflectometry, AFM, and machine-learning-based defect classification enables automated identification of nanometric voids or delamination sites before device integration.

To address yield and variability, AI-assisted wafer inspection systems now fuse optical scatterometry, electron imaging, and surface profilometry data to detect sub-10 nm process anomalies in real time[125]. These systems not only identify defects but also predict their origin based on historical process data, forming a feedback loop that continuously refines process stability.

3D integration and heterogeneous packaging

The demand for 3D integrated circuits (3D-ICs) and system-in-package (SiP) architectures has intensified the need for ultra-precision alignment and bonding at wafer and die levels. Hybrid bonding combining metallic and dielectric interfaces requires surface roughness below 0.3 nm and planarity within ±5 nm to ensure void-free contact[126].

Ultra-precision techniques such as plasma-assisted surface activation, ultraviolet/ozone cleaning, and ion-beam planarization are now integral to achieving such bonding fidelity. The use of atomic force-controlled alignment systems enables sub-50 nm overlay accuracy across large wafers. Meanwhile, the integration of ALD barrier layers and UPM-machined micro-vias ensures mechanical stability and low-resistance interconnects across stacked die layers[126].

To improve scalability, machine-learning-driven alignment control and digital twin-assisted bonding simulations are increasingly employed to predict stress evolution, void formation, and interfacial degradation during thermal cycling[127]. These data-driven methodologies bridge precision manufacturing and reliability engineering, ensuring that next-generation semiconductor assemblies meet both performance and endurance criteria.

Photonics and quantum devices

Photonic and quantum devices represent the most sensitivity-driven realization of the same ultra-precision paradigm, where sub-nanometer surface and interface imperfections directly limit optical loss, coherence time, and overall system stability. Photonics and quantum technologies represent two rapidly converging frontiers that demand atomic-scale precision in geometry, material composition, and surface quality. Optical loss, phase coherence, and quantum-state stability are highly sensitive to surface roughness, refractive index variation, and interface defects, each directly determined by manufacturing precision. Thus, UPM plays a foundational role in enabling photonic and quantum devices, where tolerances often fall below one nanometer and where even minor morphological deviations can degrade device performance by orders of magnitude[128].

Precision shaping of waveguides and resonant structures

Waveguides, resonators, and couplers form the backbone of modern photonic circuits. Their performance, defined by propagation loss, mode confinement, and coupling efficiency, depends critically on nanometric surface and sidewall smoothness. Conventional lithography followed by reactive ion etching often produces roughness-induced scattering that limits optical quality factors (Q-factors) below 10^6[129].

UPM addresses this through ion-beam polishing, laser-assisted reflow, and atomic-layer deposition (ALD) smoothing, each capable of sub-nanometer surface regulation[55]. For example, focused ion-beam (FIB) milling combined with localized laser annealing has produced silicon nitride microresonators with Q-factors exceeding 10^8 by reducing edge roughness to below 0.3 nm[130].

Furthermore, deterministic optical polishing using magnetorheological or fluid-jet finishing enables freeform optical components such as aspheric lenses and micro-mirrors for on-chip photonic coupling. These methods provide form accuracies below 10 nm and angular precision within arcseconds, essential for high-coherence laser cavities and interferometric sensors[131].

Quantum device fabrication and superconducting circuits

In quantum technologies such as superconducting qubits, trapped ions, and solid-state spin systems, the quality of the fabricated interface directly governs coherence time and noise performance. Surface roughness and chemical contamination can lead to charge noise, dielectric loss, and magnetic flux instability, limiting qubit fidelity[132].

UPM enables deterministic fabrication of superconducting microwave cavities, Josephson junctions, and photonic crystal resonators with sub-nanometer control over film thickness and interface roughness. Techniques such as ALE and plasma-assisted polishing have been employed to produce niobium and aluminum surfaces with sub-monolayer smoothness, reducing dielectric loss tangent by up to 50%[133].

The integration of ALD barrier layers and cryogenic ion-beam cleaning further enhances interface uniformity and passivation, ensuring long-term stability of superconducting circuits. Recent developments in laser-based direct writing have enabled the patterning of quantum photonic waveguides within cryo-compatible substrates, maintaining optical transparency and refractive uniformity down to 10^{-4}[134].

Integration of photonics and quantum architectures

Next-generation systems increasingly combine photonic interconnects with quantum functional elements such as single-photon sources, modulators, and detectors. This hybridization demands heterogeneous integration of dissimilar materials, for example, bonding diamond or lithium niobate to silicon or sapphire substrates with alignment tolerances below 50 nm[135].

Ultra-precision bonding techniques such as ion-beam-assisted direct bonding and surface-activated bonding (SAB) enable void-free attachment with atomically smooth interfaces. The inclusion of in situ metrology (optical coherence tomography, interferometric gap sensing) ensures alignment accuracy during bonding and post-process validation[126]. These precision capabilities support the realization of integrated quantum photonic chips, where optical and electronic functionalities coexist at nanoscale spatial alignment.

Furthermore, data-driven calibration of process parameters using reinforcement learning and digital twins enables predictive control of

refractive index gradients, mode coupling, and thermal stress distribution. Such intelligent integration frameworks are paving the way for scalable quantum–photonic foundries, where atomic-level fabrication accuracy ensures reproducible device performance across wafer-scale production[136].

MEMS/NEMS and sensor systems

MEMS and NEMS systems represent the mechanical and structural manifestation of the same ultra-precision challenge, in which geometry, surface integrity, and residual stress at the nanometer scale dominate functional performance, sensitivity, and long-term drift. Microelectromechanical (MEMS) and nanoelectromechanical (NEMS) systems form a technological bridge between electronics and mechanics, converting physical signals such as pressure, vibration, and acceleration into electrical outputs. The sensitivity, bandwidth, and long-term reliability of these devices are governed by geometric uniformity, surface roughness, and residual stress at the micro- and nanoscales. UPM plays a critical role in realizing MEMS/NEMS devices with consistent performance, enabling sub-nanometer form control, defect-free interfaces, and deterministic alignment of functional layers[137].

Integration of ultra-precision machining and thin-film deposition

The fabrication of high-performance MEMS/NEMS devices often demands hybrid workflows combining mechanical microstructuring and thin-film processing. Ultra-precision machining using diamond turning or micro-grinding produces dimensionally accurate substrates and housings with surface roughness below 10 nm Ra, ensuring high mechanical Q-factors and stable boundary conditions[138].

Following structural formation, atomic-layer deposition (ALD) or plasma-enhanced chemical vapor deposition (PECVD) can be employed to form conformal coatings and functional films on micro-scale structures. ALD's self-limiting growth behavior ensures uniformity on complex geometries such as resonator tethers or cantilevers, where film thickness variations could induce stress gradients or frequency drift[139].

Recent developments in ultra-precision laser trimming and ion-beam surface tuning allow post-fabrication correction of mass imbalance and stiffness non-uniformity at the nanogram scale. These deterministic finishing steps enable batch-level tuning of resonant frequencies within ±0.01%, critical for high-throughput MEMS gyroscopes and resonators.

Ultra-sensitive transducers and resonators

Achieving high sensitivity in MEMS/NEMS devices depends on minimizing mechanical damping and maintaining structural integrity under environmental stress. Ultra-precision manufacturing contributes through surface energy minimization, defect suppression, and interface quality control. For instance, in capacitive or piezoelectric accelerometers, reducing sidewall roughness to below 5 nm decreases electrostatic noise and parasitic capacitance variation[140].

Similarly, in piezoresistive pressure sensors, deterministic polishing and planarization of the diaphragm surface ensure consistent stress distribution and high signal linearity. Diamond-turned silicon diaphragms exhibit less than 0.2% nonlinearity even at full-scale deflection due to improved thickness uniformity[141]. For resonant NEMS devices, surface contamination and adsorbed layers significantly affect frequency stability. Therefore, plasma-based surface cleaning and passivation techniques derived from UPM are now standard practice to maintain long-term drift below 10 ppm[142].

Hybrid packaging and environmental stability

Ultra-precision packaging is essential for preserving the sensitivity and longevity of MEMS/NEMS devices. Conventional dies attach, and bonding processes introduce residual stresses that shift resonance frequencies and degrade sensor performance. UPM techniques such as laser-assisted bonding, surface-activated bonding (SAB), and micro-lapped alignment surfaces enable hermetic encapsulation with nanometric flatness and controlled thermal expansion mismatch[143].

For high-end inertial sensors and micro-mirrors, hybrid integration of UPM-machined metallic housings with thin-film MEMS dies has demonstrated thermal stability improvements exceeding 40% compared with conventional packaging[144]. The combination of precision machining and ALD-based surface sealing also enhances long-term vacuum retention, reducing damping losses in resonant cavities.

Emerging packaging methodologies leverage AI-assisted alignment systems and digital-twin simulations to predict deformation and stress accumulation during bonding or thermal cycling. These predictive frameworks ensure that sensor arrays maintain geometric consistency and cross-axis sensitivity below 0.1%, a benchmark for next-generation navigation-grade MEMS sensors[119].

Flexible and heterogeneous integration

Flexible and heterogeneous systems extend the ultra-precision paradigm into mechanically compliant and multi-material platforms, where nanoscale interface control, bonding fidelity, and surface integrity become the dominant constraints on reliability and functional integration. Flexible and heterogeneous integration represents a transformative direction in electronics and photonics manufacturing, merging disparate materials, rigid semiconductors, polymers, glass, and metal foils into unified functional systems. Unlike conventional wafer-based fabrication, these systems demand ultra-precision alignment, nanoscale bonding control, and conformal interface engineering to maintain electrical and optical continuity during mechanical deformation. UPM provides the deterministic control and adaptive feedback necessary to achieve this integration while ensuring reliability under bending, thermal, and dynamic stress[145].

Nano-alignment and bonding across dissimilar materials

The integration of materials with mismatched coefficients of thermal expansion (CTE) and mechanical moduli introduces significant challenges in alignment and bonding. Ultra-precision systems employ active alignment stages with sub-10 nm resolution and interferometric feedback to ensure positional accuracy during assembly[146].

Surface-activated bonding (SAB), plasma-assisted bonding, and ultraviolet-curing adhesive bonding are commonly utilized to form void-free joints at temperatures below 200 °C, minimizing interfacial stress while maintaining nanometer-level planarity. For polymer-semiconductor and glass–metal combinations, pre-bonding surface conditioning through ion-beam cleaning or ALD passivation improves adhesion energy and reduces defect density[147].

Recent developments in laser-based localized bonding combine precision energy delivery with optical feedback to achieve spatially selective joining of functional areas without damaging temperature-sensitive regions. This technique enables monolithic integration of rigid chips on flexible polymer substrates while preserving nanoscale electrical continuity[148].

Ultra-precision fabrication for flexible photonic and electronic platforms

Flexible photonic interposers, micro-LED arrays, and wearable biosensors require fabrication processes that maintain optical and electrical performance under mechanical strain. Ultra-precision machining of flexible substrates, such as polyimide and polyethylene naphthalate (PEN), provides surface smoothness below 5 nm Ra, reducing scattering losses in optical waveguides and ensuring uniform field confinement[149].

For electronics, additive-subtractive hybrid UPM enables micro-patterned metallic interconnects and embedded electrodes with linewidth control below 1 μm. Integration with atomic-layer-deposited dielectric barriers prevents metal diffusion and enhances bending endurance. In flexible display and sensor manufacturing, deterministic laser ablation and inkjet-assisted nanoparticle printing are combined to produce transparent conductive networks with sheet resistances below 30 Ω/sq while maintaining >90% optical transmittance[150].

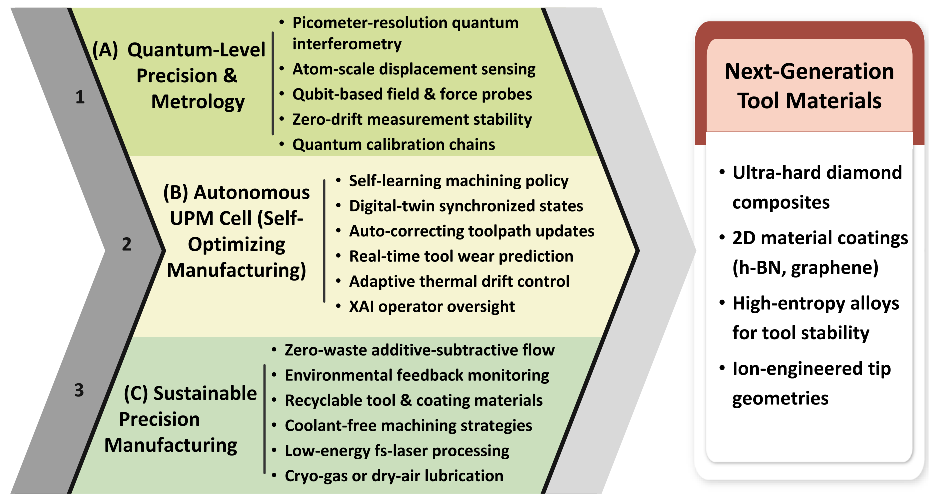

Fig. 10 | Future prospects: toward sustainable and quantum-level precision.

These processes collectively deliver the mechanical compliance and electrical precision required for next-generation soft robotics, biomedical implants, and human-machine interfaces.

Case study: ultra-precision bonding in flexible photonic interposers

A representative example of ultra-precision integration is the fabrication of flexible photonic interposer platforms that route optical and electrical signals through polymeric substrates. The process involves sequential deposition of metal and dielectric layers, ultra-precision laser micromachining of optical vias, and alignment of photonic chips with a tolerance better than 50 nm[150].

In this workflow, interferometric alignment combined with real-time OCT ensures accurate overlay between polymer waveguides and silicon photonic dies. Post-bonding, deterministic polishing is used to remove residual misalignment layers, achieving optical coupling losses below 0.2 dB. The resulting hybrid system demonstrates bending radii below 5 mm without optical performance degradation, a feat unattainable without sub-nanometer bonding precision and adaptive feedback control[151].

The success of such processes underscores the potential of UPM-enabled flexible systems in photonic computing, medical diagnostics, and wearable optoelectronics, where scalability and geometric precision must coexist with mechanical resilience.

Challenges and future prospects

The future of UPM will be shaped not by a single dominant technology, but by the selective integration and consolidation of existing approaches. It is therefore useful to distinguish between technologies that are likely to become industrial workhorses, those that will remain indispensable but niche, and those whose role will gradually shift toward embedded or supporting functions in scalable manufacturing systems. UPM has advanced dramatically over the past two decades, yet several technological and scientific barriers still constrain its scalability, sustainability, and autonomy. Achieving atomic-level reproducibility across diverse materials, environments, and production scales remains a formidable challenge. This section critically examines the main obstacles, technical, environmental, and systemic, and outlines emerging directions toward sustainable, intelligent, and quantum-informed ultra-precision manufacturing (Fig. 10).

Technical barriers

Despite extensive progress in tool design, process modeling, and environmental control, tool degradation, thermal fluctuation, and process repeatability remain persistent limitations. Diamond tools, though exceptionally hard, undergo gradual wear and graphitization when machining ferrous or carbide-rich materials. Such degradation introduces micro-topographical deviations that accumulate as form errors beyond 10 nm over long machining cycles[152]. Developing novel superhard tool materials such as chemical-vapor-deposited (CVD) diamond composites or boron–nitride-based ceramics is, therefore, critical for extending tool life and maintaining atomic-scale consistency.

Thermal management presents another key challenge. Even small perturbations in temperature can result in asymmetric expansion or contraction in the motion systems, resulting in nanometric deviations quality of finished machined part. While environmental isolation and cryogenic cooling can help, they remain energy-intensive and cost-prohibitive for large-scale adoption. Advanced compensation strategies leveraging AI-based thermal drift prediction and digital twins are being developed to achieve active stabilization without extensive environmental conditioning[153].

At the process level, cross-scale modeling continues to hinder predictive control. The coupling of quantum-level interactions (e.g., atomic dislocation, surface diffusion) with continuum-scale phenomena (heat transfer, tool dynamics) defies straightforward simulation. Bridging these scales will require multi-physics, multi-resolution computational frameworks, validated by high-speed, high-resolution in situ measurements[154].

A central unresolved challenge in ultra-precision manufacturing is not only achieving higher precision, but achieving it simultaneously with high throughput, robustness, and economic viability, also referred collectively as "Precision-at-Scale". Many precise techniques remain inherently slow and costly, while more scalable methods struggle to reach atomic-level precision. Bridging this gap needs deeper integration of multi-stage process chains, hybrid machine architectures, and AI-driven process orchestration.

Sustainable ultra-precision manufacturing

Sustainability is emerging as a defining imperative in advanced manufacturing. Conventional UPM processes, such as oil-based lapping, slurry polishing, and vacuum plasma systems, are energy-intensive systems and lead to significant waste. Transitioning toward environmentally green manufacturing requires innovations in both materials and process design.

Dry or lubricant-free machining, enabled by gas bearings and low-friction coatings, can eliminate oil contamination and reduce maintenance overhead. Similarly, low-energy ultrafast lasers and cold-ablation beam systems minimize thermal load and extend component lifespan. Researchers are also exploring bio-derived abrasives and recyclable tool composites as a way to reduce dependency on rare-earth or toxic materials[155]. In this spirit, researchers have recently explored pathways to develop critical-raw-material (CRM) free alloys merely using Machine Learning approaches[156].

Closed-loop recycling of cutting fluids, tool materials, and process by-products is being integrated into next-generation UPM facilities.

Combining life-cycle sustainability assessment (LCSA) with real-time data analytics enables quantitative tracking of carbon and energy footprints, providing a foundation for sustainable process certification. The synergy between precision engineering and green design is gradually shifting UPM from a high-resource discipline to an eco-efficient manufacturing ecosystem[155,157].

Toward autonomous and quantum-level precision

The next frontier for UPM lies in autonomous, self-calibrating systems capable of quantum-level precision where measurement uncertainty approaches the physical limits imposed by atomic vibrations and quantum noise. This transformation requires three enabling pillars: quantum sensors, AI-driven autonomy, and human–machine collaboration.

Quantum-enhanced metrology, based on interferometric displacement sensors and entangled-photon interferometers, promises displacement sensitivity in the picometer range, surpassing classical optical methods by an order of magnitude[158]. Integrating such sensors into machining platforms will provide real-time feedback with near-zero measurement noise, enabling unprecedented control over material removal and positioning accuracy[159].

AI-driven autonomy will enable systems that self-diagnose and self-correct without human intervention. Reinforcement learning agents, trained on digital twins and process history, will dynamically adjust parameters to maintain optimal precision even under environmental drift or material variation. Early demonstrations of self-calibrating machining cells already show form error correction below 2 nm without operator input[160].

Finally, human-machine collaboration under Industry 5.0 envisions operators as strategic supervisors rather than manual controllers. Explainable AI interfaces and haptic feedback systems will allow engineers to interact intuitively with digital twins, guiding decision-making based on physics-informed recommendations rather than trial-and-error. This collaborative paradigm will be crucial for ensuring transparency, safety, and trust in autonomous precision manufacturing[107].

Death valley of technology readiness level (TRL)

A central challenge in ultra-precision manufacturing is the "valley of death" between Technology Readiness Levels (TRLs), where many promising discoveries remain confined to the laboratory due to insufficient investment to scale them for commercial deployment. Therefore, addressing the gap between laboratory-level performance and industrial-scale manufacturability is now critical. Many precision manufacturing techniques demonstrate outstanding results under controlled experimental conditions, yet struggle to meet the simultaneous requirements of high throughput and process stability. In practice, industrial adoption is often limited not by ultimate precision, but by the cumulative effects of process drift, equipment downtime, consumable costs, yield loss, and integration complexity[161].

This creates a fundamental gap between precision and productivity: techniques such as FIB, ALD, scanning probe lithography (SPL), or ALE offer unmatched control, but at throughput levels that are incompatible with most high-volume manufacturing scenarios. Conversely, more scalable techniques, such as laser processing, must continuously balance speed, stability, and damage control. Overcoming this dichotomy will require not only incremental process improvements, but also new machine architectures, parallelization strategies, predictive maintenance enabled by AI, and tighter integration of trustworthy digital twins to ensure stable, economical operation over extended production cycles[162].

Bottlenecks to scale ultra-precision manufacturing from laboratory to wafer-scale and high-volume production

Although many ultra-precision manufacturing techniques have demonstrated sub-nanometer or even atomic-scale capability in laboratory environments, translating this performance to wafer-scale or high-volume manufacturing remains a fundamental challenge. In practice, the dominant limitation is not the ultimate achievable resolution, but the difficulty of maintaining such precision simultaneously across large areas, over long durations, and at economically viable throughput. This gap between demonstrated capability and manufacturable performance represents the central bottleneck of the field. One of the most pervasive barriers is throughput and serial processing[163]. Many of the highest-precision techniques are intrinsically slow and can only be performed in series. While these methods offer unmatched control over local geometry and interfaces, their processing rates are fundamentally incompatible with wafer-scale or high-volume production unless massive parallelization or radically new machine architectures are introduced[164].

A second major bottleneck is long-term process stability and drift. As process durations extend from minutes to hours or days for large-area or batch production, nanometer-scale thermal drift, mechanical creep, vibration, and environmental fluctuations accumulate into form errors that can exceed the target tolerances. Even in ultra-precision machining and polishing systems, maintaining sub-10 nm accuracy over wafer-scale areas requires extensive environmental control, frequent recalibration, and continuous metrology feedback, all of which reduce effective throughput and increase system complexity[155]. Tool wear and consumable degradation constitute another critical scaling barrier. Diamond tool wear in mechanical ultra-precision machining, chamber wall conditioning in plasma and atomic-layer systems, and beam source degradation in ion and electron beam tools all introduce gradual, often nonlinear process drift. At laboratory scale, such effects can be mitigated through frequent intervention, but in high-volume manufacturing, they directly translate into yield loss, downtime, and escalating operating costs[165].

Contamination, redeposition, and defect accumulation become increasingly severe as the processed area and production volume increase. Beam-based processes suffer from redeposition and implantation effects, while chemical and atomic-layer processes are highly sensitive to precursor purity and particle generation. At the wafer scale, even extremely low defect densities can become yield-limiting, making contamination control and tool conditioning dominant cost and reliability drivers. A further fundamental constraint is metrology bandwidth and feedback latency. While sub-nanometer measurement capability exists, embedding metrology into high-throughput production tools with sufficient spatial and temporal resolution remains extremely challenging. As feature sizes shrink and tolerances tighten, the manufacturing system increasingly becomes metrology-limited rather than process-limited[166].

Finally, system-level complexity, uptime, and cost of ownership impose hard economic limits on scalability. Many ultra-precision platforms require vacuum environments, multi-physics control, vibration isolation, and tightly controlled thermal conditions, leading to high capital cost and operational overhead. At an industrial scale, these factors often dominate decision-making more strongly than ultimate achievable precision. Taken together, these constraints explain why many ultra-precision techniques remain confined to high-value, low-volume applications. Overcoming these bottlenecks will require not only incremental process improvements, but new paradigms in machine architecture, massive parallelization, AI-driven drift compensation, predictive maintenance, and tightly integrated metrology[167,168].

Technology maturation pathways and strategic priorities (5–10 year outlook)

While a wide range of ultra-precision manufacturing technologies have demonstrated impressive laboratory-level capabilities, their future impact will be determined not only by ultimate achievable precision, but by scalability, robustness, and economic viability. Over the next 5–10 years, this field is expected to undergo a consolidation wherein certain technologies will mature into broadly deployable industrial platforms, others remain confined to niche applications, and some will either be absorbed into hybrid systems or gradually lose standalone relevance[169].

Technologies likely to mature into mainstream industrial platforms include advanced ultra-precision machining combined with in situ metrology and AI-based drift compensation, hybrid additive-subtractive manufacturing architectures, and atomic-layer processes tightly integrated

Table 1 | Expected technology evolution in ultra-precision manufacturing over the next 5–10 years

Technology class	Likely trajectory	Primary role in 5–10 years
Ultra-precision machining + AI + in situ metrology	Mainstream industrial platform	High-precision form generation and finishing
Atomic-layer processes (ALD/ALE)	Mainstream, but as part of integrated chains	Interface engineering and functional layers
Hybrid additive–subtractive systems	Strong growth/partial mainstream	Complex geometry + precision finishing
FIB/EB processing	Remain niche	Trimming, repair, prototyping, failure analysis
Ultrafast femtosecond laser nanoprocessing	Selective industrialization	Hard/brittle materials, selective structuring
Standalone exotic lab-scale methods	Absorbed or phased out	Embedded into hybrid systems or replaced

into high-throughput process chains. These approaches already possess partial industrial maturity and directly address the dominant bottlenecks of stability, yield, and reproducibility. Continued progress in machine architecture, sensor integration, and closed-loop control is expected to make these systems increasingly autonomous, reliable, and scalable within the next decade[170].

Technologies likely to remain specialized or niche include focused ion and electron beam processing, as well as certain ultrafast laser nanostructuring approaches. Although these methods offer unmatched flexibility and resolution, their intrinsically serial nature, limited throughput, and high cost of ownership make them structurally unsuited for high-volume manufacturing. Their future role will therefore remain concentrated in mask repair, device trimming, failure analysis, prototyping, and high-value and low-volume components[171].

Technologies whose standalone relevance may diminish are those that cannot simultaneously improve throughput, stability, and cost efficiency, and will instead be absorbed into hybrid platforms or multi-stage process chains. In many cases, their physical principles will persist, but not as isolated manufacturing solutions. Instead, they will function as embedded modules within integrated manufacturing ecosystems[172].

From a research perspective, the highest-impact directions over the next decade are expected to be: (1) hierarchical and hybrid process-chain integration, (2) massive parallelization and new machine architectures for throughput scaling, (3) in situ, multi-modal metrology and AI-driven self-calibration, (4) digital twins for predictive control and yield management[173], and (5) sustainable, low-footprint ultra-precision manufacturing concepts. In contrast, purely incremental improvements in ultimate resolution without corresponding gains in stability, scalability, or cost-effectiveness are unlikely to translate into widespread industrial impact (Table 1).

Conclusions

Ultra-precision manufacturing (UPM) has evolved from a niche discipline of optical fabrication into a cornerstone of next-generation electronic, photonic, and quantum technologies. By uniting deterministic material removal, atomic-scale surface engineering, and intelligent feedback control, UPM now enables fabrication accuracies that approach the physical limits of matter organization. Across diverse applications from semiconductor wafer planarization and MEMS packaging to photonic resonators and flexible electronics, the fusion of mechanical, chemical, and data-driven precision has fundamentally redefined what is manufacturable.

The current landscape reflects a paradigm shift: precision is no longer achieved solely through mechanical refinement but through the coalescence of physics-based modeling, machine intelligence, and adaptive metrology. The integration of explainable AI, digital twins, and quantum-level sensors is driving a transition from operator-dependent craftsmanship to autonomous, self-calibrating manufacturing ecosystems. This evolution promises reproducibility, scalability, and sustainability on a scale previously unattainable during nanometric fabrication.

Future ultra-precision platforms will increasingly operate as closed-loop intelligent systems, capable of sensing, predicting, and correcting in real time, while minimizing material waste and energy consumption. Their development will require interdisciplinary collaboration across materials science, computational engineering, data analytics, and system integration. As manufacturing enters the quantum era, the ultimate vision of UPM is clear to enable the deterministic control of matter at the atomic scale in a sustainable, intelligent, and fully autonomous manner.

Data availability

No datasets were generated or analyzed during the current study.

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References

1. Manvi, M. & Mruthyunjaya Swamy, K. B. Microelectronic materials, microfabrication processes, micromechanical structural configuration based stiffness evaluation in MEMS: a review. *Microelectron. Eng.* **263**, 111854 (2022).
2. Fazeli Jadidi, M. et al. Distribution of shallow NV centers in diamond revealed by photoluminescence spectroscopy and nanomachining. *Carbon* **167**, 114–121 (2020).
3. Fan, P. et al. Scanning probe lithography: state-of-the-art and future perspectives. *Micromachines* **13**, 228 (2022).
4. Madou, M. J. *Manufacturing Techniques for Microfabrication and Nanotechnology* (CRC Press, 2011).
5. Fischer, A. C. et al. Integrating MEMS and ICs. *Microsyst. Nanoeng.* **1**, 1–16 (2015).
6. Wong, H. & Iwai, H. The road to miniaturization. *Phys. World* **18**, 40–44 (2005).
7. Chiang, Y.-C. et al. Enhancing the high-frequency signal performance through surface morphological modification of Cu interconnects. *Measurement* **250**, 117071 (2025).
8. Liao, W. et al. Interface engineering of two-dimensional transition metal dichalcogenides towards next-generation electronic devices: recent advances and challenges. *Nanoscale Horiz.* **5**, 787–807 (2020).
9. Lin, L., Kollipara, P. S. & Zheng, Y. Digital manufacturing of advanced materials: challenges and perspective. *Mater. Today* **28**, 49–62 (2019).
10. Yip, W. S., To, S. & Zhou, H. T. Current status, challenges and opportunities of sustainable ultra-precision manufacturing. *J. Intell. Manuf.* **33**, 2193–2205 (2022).
11. Evans, C. J. Precision engineering: an evolutionary perspective. *Philos. Trans. A Math. Phys. Eng. Sci.* **370**, 3835–3851 (2012).
12. Abdulkadir, L. N. et al. Ultra-precision diamond turning of optical silicon—a review. *Int. J. Adv. Manuf. Technol.* **96**, 173–208 (2018).
13. Liu, Q., Chen, M., Cheng, J. & Luo, X. Ultra-precision manufacturing technology for difficult-to-machine materials. *Materials* **16**, 4322 (2023).
14. Geng, Z., Huang, N., Castelli, M. & Fang, F. Polishing approaches at atomic and close-to-atomic scale. *Micromachines* **14**, 343 (2023).
15. Wang, T. et al. Ion beam figuring system for synchrotron x-ray mirrors achieving sub-0.2-µrad and sub-0.5-nm root mean square. *Nanomanuf. Metrol.* **6**, 20 (2023).

16. Pan, Y. et al. New insights into the methods for predicting ground surface roughness in the age of digitalisation. *Precis. Eng.* **67**, 393–418 (2021).
17. Nagayama, K. & Yan, J. Measurement and compensation of tool contour error using white light interferometry for ultra-precision diamond turning of freeform surfaces. *Int. J. Autom. Technol.* **14**, 654–664 (2020).
18. Gao, W., Tano, M., Araki, T., Kiyono, S. & Park, C. H. Measurement and compensation of error motions of a diamond turning machine. *Precis. Eng.* **31**, 310–316 (2007).
19. Gao, W. et al. On-machine and in-process surface metrology for precision manufacturing. *CIRP Ann.* **68**, 843–866 (2019).
20. Yuan, J., Lyu, B., Hang, W. & Deng, Q. Review on the progress of ultra-precision machining technologies. *Front. Mech. Eng.* **12**, 158–180 (2017).
21. Seid Ahmed, Y. & Amorim, F. L. Advances in computer numerical control geometric error compensation: integrating AI and on-machine technologies for ultra-precision manufacturing. *Machines* **13**, 140 (2025).
22. Kim, J. H. et al. Advanced measurement and diagnosis of the effect on the underlayer roughness for industrial standard metrology. *Sci. Rep.* **9**, 1018 (2019).
23. Córdoba, R., Orús, P., Strohauer, S., Torres, T. E. & De Teresa, J. M. Ultra-fast direct growth of metallic micro-and nano-structures by focused ion beam irradiation. *Sci. Rep.* **9**, 14076 (2019).
24. Fan, P., Goel, S., Luo, X. & Upadhyaya, H. M. Atomic-scale friction studies on single-crystal gallium arsenide using atomic force microscope and molecular dynamics simulation. *Nanomanuf. Metrol.* **5**, 39–49 (2022).
25. Fan, P. et al. Origins of ductile plasticity in a polycrystalline gallium arsenide during scratching: MD simulation study. *Appl. Surf. Sci.* **552**, 149489 (2021).
26. Khatri, N. et al. Single-step precision manufacturing of ZnSe lenses for FLIR thermal imaging: from atomic insights to lab-scale fabrication and integration. *J. Manuf. Process* **142**, 468–481 (2025).
27. Yin, J., Bai, Q., Goel, S., Zhou, P. & Zhang, B. An analytical model to predict the depth of sub-surface damage for grinding of brittle materials. *CIRP J. Manuf. Sci. Technol.* **33**, 454–464 (2021).
28. Goel, S. The current understanding on the diamond machining of silicon carbide. *J. Phys. D Appl. Phys.* **47**, 243001 (2014).
29. Fang, F., Zhang, X., Weckenmann, A., Zhang, G. & Evans, C. Manufacturing and measurement of freeform optics. *CIRP Ann.* **62**, 823–846 (2013).
30. Ameli Kalkhoran, S. N., Vahdati, M., Zhang, Z. & Yan, J. Influence of wax lubrication on cutting performance of single-crystal silicon in ultraprecision microgrooving. *Int. J. Precis. Eng. Manuf. Green Technol.* **8**, 611–624 (2020).
31. Goel, S., Luo, X., Agrawal, A. & Reuben, R. L. Diamond machining of silicon: a review of advances in molecular dynamics simulation. *Int. J. Mach. Tools Manuf.* **88**, 131–164 (2015).
32. Xu, Z. et al. A review: insight into smart and sustainable ultra-precision machining augmented by intelligent IoT. *J. Manuf. Syst.* **74**, 233–251 (2024).
33. Goel, S., Luo, X., Comley, P., Reuben, R. L. & Cox, A. Brittle–ductile transition during diamond turning of single crystal silicon carbide. *Int. J. Mach. Tools Manuf.* **65**, 15–21 (2013).
34. Kovalchenko, A. M., Goel, S., Zakiev, I. M., Pashchenko, E. A. & Al-Sayegh, R. Suppressing scratch-induced brittle fracture in silicon by geometric design modification of the abrasive grits. *J. Mater. Res. Technol.* **8**, 703–712 (2019).
35. Geng, Z., Tong, Z. & Jiang, X. Review of geometric error measurement and compensation techniques of ultra-precision machine tools. *Light Adv. Manuf.* **2**, 211–227 (2021).
36. Xu, H. et al. In situ measurement of spindle radial error for ultra-precision machining based on three-point method. *Micromachines* **14**, 653 (2023).
37. Goel, S., Martinez, F. D., Chavoshi, S. Z., Khatri, N. & Giusca, C. Molecular dynamics simulation of the elliptical vibration-assisted machining of pure iron. *J. Micromanuf.* **1**, 6–19 (2018).
38. Goel, S., Kovalchenko, A., Stukowski, A. & Cross, G. Influence of microstructure on the cutting behaviour of silicon. *Acta Mater.* **105**, 464–478 (2016).
39. Ameli Kalkhoran, S. N., Vahdati, M. & Yan, J. Molecular dynamics investigation of nanometric cutting of single-crystal silicon using a blunt tool. *JOM* **71**, 4296–4304 (2019).
40. Higginbottom, D. B. et al. Fabrication of ultrahigh-precision hemispherical mirrors for quantum-optics applications. *Sci. Rep.* **8**, 221 (2018).
41. Li, D., Tong, Z., Jiang, X., Blunt, L. & Gao, F. Calibration of an interferometric on-machine probing system on an ultra-precision turning machine. *Measurement* **118**, 96–104 (2018).
42. Chen, Z. et al. Development of an on-machine measurement system for ultra-precision machine tools using a chromatic confocal sensor. *Precis. Eng.* **74**, 232–241 (2022).
43. Zhang, X. et al. Challenges and strategies in high-accuracy manufacturing of the world's largest SiC aspheric mirror. *Appl. Sci.* **11**, 310 (2022).
44. Feng, J. et al. A review of an investigation of the ultrafast laser processing of brittle and hard materials. *Materials* **17**, 3657 (2024).
45. Liu, H., Lin, W. & Hong, M. Hybrid laser precision engineering of transparent hard materials: challenges, solutions and applications. *Light Sci. Appl.* **10**, 162 (2021).
46. Park, M., Gu, Y., Mao, X., Grigoropoulos, C. P. & Zorba, V. Mechanisms of ultrafast GHz burst fs laser ablation. *Sci. Adv.* **9**, eadf6397 (2023).
47. Höflich, K. et al. Roadmap for focused ion beam technologies. *Appl. Phys. Rev*. **10**, https://doi.org/10.1063/5.0162597 (2023).
48. Utke, I., Michler, J., Winkler, R. & Plank, H. Mechanical properties of 3D nanostructures obtained by focused electron/ion beam-induced deposition: a review. *Micromachines* **11**, 397 (2020).
49. Priebe, A. & Michler, J. Review of recent advances in gas-assisted focused ion beam time-of-flight secondary ion mass spectrometry (FIB-TOF-SIMS). *Materials* **16**, 2090 (2023).
50. Rehman, H. U. et al. Electron backscatter diffraction analysis combined with NanoSIMS U–Pb isotope data reveal intra-grain plastic deformation in zircon and its effects on U–Pb age: examples from Himalayan eclogites, Pakistan. *Eur. J. Mineral.* **35**, 1079–1090 (2023).
51. Luo, X. et al. Laser-assisted grinding of reaction-bonded SiC. *J. Micromanuf.* **3**, 93–98 (2020).
52. Liu, C. et al. Cutting mechanism of reaction-bonded silicon carbide in laser-assisted ultra-precision machining. *Int. J. Mach. Tools Manuf.* **203**, 104219 (2024).
53. Dennis, A., Goel, S., Al-Sayegh, R. & O'Neill, W. The importance of wavelength for tight temperature control during μ-laser-assisted machining. *J. Micromanuf.* **4**, 93–98 (2021).
54. Maier, P., Rupp, S., Lettner, N., Denschlag, J. H. & Kubanek, A. Fabrication of customized low-loss optical resonators by combination of FIB-milling and CO(2) laser smoothing. *Opt. Express* **33**, 19205–19219 (2025).
55. Lee, T. Y. et al. Advances in core technologies for semiconductor manufacturing: applications and challenges of atomic layer etching, neutral beam etching and atomic layer deposition. *Nanoscale Adv.* **7**, 2796–2817 (2025).
56. Feng, Y. et al. Process condition optimization for atomic layer etching: insights into surface phenomena from multiscale computational framework and experiments. *Vacuum* 114864 https://doi.org/10.1016/j.vacuum.2025.114864 (2025).

57. Anders, A. A structure zone diagram including plasma-based deposition and ion etching. *Thin Solid Films* **518**, 4087–4090 (2010).
58. Lee, S., Lee, G., Oh, J. & An, J. Novel atomic layer processes for semiconductor manufacturing: area selective deposition, atomic layer annealing, and atomic layer etching. *Int. J. Precis. Eng. Man.* **26**, 2551–2571 (2025).
59. Kunene, T. J., Tartibu, L. K., Ukoba, K. & Jen, T.-C. Review of atomic layer deposition process, application and modeling tools. *Mater. Today Proc.* **62**, S95–S109 (2022).
60. Chen, Y. et al. Multiscale CFD modelling for conformal atomic layer deposition in high aspect ratio nanostructures. *Chem. Eng. J.* **472**, 144944 (2023).
61. Chang, Y. et al. Atomic-layer-deposited Al2O3 and HfO2 on GaN: a comparative study on interfaces and electrical characteristics. *Microelectron. Eng.* **88**, 1207–1210 (2011).
62. van de Poll, M. et al. Plasma-enhanced spatial atomic layer deposition on 2D and 3D surface topologies: the case of amorphous and crystalline TiO(2). *J. Phys. Chem. C Nanomater Interfaces* **129**, 3310–3320 (2025).
63. McGuinness, E. K., Liu, Y., Ramprasad, R. & Losego, M. D. Quartz crystal microbalance gravimetry measurements of the sorption of trimethylaluminum into polystyrene and poly (methyl methacrylate). *Mater. Chem. Phys.* **294**, 127026 (2023).
64. Fang, C., Cao, Y., Wu, D. & Li, A. Thermal atomic layer etching: mechanism, materials and prospects. *Prog. Nat. Sci. Mater. Int.* **28**, 667–675 (2018).
65. Chittock, N. J. et al. Investigation of the atomic layer etching mechanism for Al(2)O(3) using hexafluoroacetylacetone and H(2) plasma. *J. Mater. Chem. C Mater.* **13**, 1345–1358 (2025).
66. Han, Z., Vehkamaki, M., Leskela, M. & Ritala, M. Combining focused ion beam and atomic layer deposition in nanostructure fabrication. *Nanotechnology* **25**, 115302 (2014).
67. Yanguas-Gil, A. & Elam, J. W. Machine learning and atomic layer deposition: predicting saturation times from reactor growth profiles using artificial neural networks. *J. Vac. Sci. Technol. A* **40**, https://doi.org/10.1116/6.0001973 (2022).
68. In't Veld, B. H. et al. Micro additive manufacturing using ultra short laser pulses. *CIRP Ann.* **64**, 701–724 (2015).
69. Goh, G. D., Wong, K. K., Tan, N., Seet, H. L. & Nai, M. L. S. Large-format additive manufacturing of polymers: a review of fabrication processes, materials, and design. *Virtual Phys. Prototyp.* **19**, e2336160 (2024).
70. Afridi, A., Al Rashid, A. & Koç, M. Recent advances in the development of stereolithography-based additive manufacturing processes: a review of applications and challenges. *Bioprinting* **43**, e00360 (2024).
71. Zhu, Y. et al. Recent advancements and applications in 3D printing of functional optics. *Addit. Manuf.* **52**, 102682 (2022).
72. McCann, R. et al. In-situ sensing, process monitoring and machine control in laser powder bed fusion: a review. *Addit. Manuf.* **45**, 102058 (2021).
73. Guerra, M. G. et al. High resolution-optical tomography for in-process layerwise monitoring of a laser-powder bed fusion technology. *Addit. Manuf.* **55**, 102850 (2022).
74. Goel, S., Katiyar, N. K., Khatri, N., Alsayegh, R. & Agrawal, A. Diamond machining of additively manufactured Ti6Al4V: novel chip formation and friction-induced welding mechanism. *J. Proc. Inst. Mech. Eng. B J. Eng. Manufact*. 1–9 https://doi.org/10.1177/09544054251405628 (2025).
75. Wu, B. et al. Ion beam smoothing of fused silica at atomic-scale assisted by damage recovery using inductively coupled plasma. *Precis. Eng.* **90**, 71–80 (2024).
76. Chavoshi, S. Z., Goel, S. & Morantz, P. J. M. Current trends and future of sequential micro-machining processes on a single machine tool. *Mater. Des.* **127**, 37–53 (2017).
77. Wang, R., Standfield, B., Dou, C., Law, A. C. & Kong, Z. J. Real-time process monitoring and closed-loop control on laser power via a customized laser powder bed fusion platform. *Addit. Manuf.* **66**, 103449 (2023).
78. Vallabh, C. K. P. & Zhao, X. Melt pool temperature measurement and monitoring during laser powder bed fusion based additive manufacturing via single-camera two-wavelength imaging pyrometry (STWIP). *J. Manuf. Process* **79**, 486–500 (2022).
79. Chen, Y.-P. et al. Real-time decision-making for digital twin in additive manufacturing with model predictive control using time-series deep neural networks. *J. Manuf. Syst.* **80**, 412–424 (2025).
80. Mann, S. et al. Connected, digitalized wire arc additive manufacturing: utilizing data in the internet of production to enable industrie 4.0. *Sci. Rep.* **15**, 38672 (2025).
81. Baumann, C. et al. Comparison of three hybrid metal additive-subtractive manufacturing processes. *CIRP Ann.* https://doi.org/10.1016/j.cirp.2025.04.074 (2025).
82. Karimi, K. et al. A thorough review of emerging technologies in micro- and nanochannel fabrication: limitations, applications, and comparison. *Micromachines* **15**, 1274 (2024).
83. Zhou, L. et al. Additive manufacturing: a comprehensive review. *Sensors* **24**, 2668 (2024).
84. Catalucci, S., Thompson, A., Piano, S., Branson III, D. T. & Leach, R. Optical metrology for digital manufacturing: a review. *Int. J. Adv. Manuf. Technol.* **120**, 4271–4290 (2022).
85. Zhang, J. & Wang, M. Alternative micro/nanofabrication approaches for wearable electronics. *Chem. Rev.* **126**, 1686–1762 (2026).
86. Fang, F. et al. Towards atomic and close-to-atomic scale manufacturing. *Int. J. Extrem. Manuf.* **1**, 012001 (2019).
87. Su, R. & Leach, R. Physics-based virtual coherence scanning interferometer for surface measurement. *Light Adv. Manuf.* **2**, 120–135 (2021).
88. Kim, J.-H., Yoon, S.-W., Lee, J.-H., Ahn, W.-J. & Pahk, H.-J. New algorithm of white-light phase shifting interferometry pursing higher repeatability by using numerical phase error correction schemes of pre-processor, main processor, and post-processor. *Opt. Lasers Eng.* **46**, 140–148 (2008).
89. Leach, R. *Fundamental Principles of Engineering Nanometrology* (Elsevier, 2014).
90. Mazzeo, A., Stein, A., Trumper, D. & Hocken, R. Atomic force microscope for accurate dimensional metrology. *Precis. Eng.* **33**, 135–149 (2009).
91. Lawrence, J. et al. Combining high-resolution scanning tunnelling microscopy and first-principles simulations to identify halogen bonding. *Nat. Commun.* **11**, 2103 (2020).
92. Kandel, S. et al. Imaging extended single crystal lattice distortion fields with multi-peak Bragg ptychography. *Opt. Express* **32**, 19594–19610 (2024).
93. Kawado, S. et al. Three-dimensional structure of dislocations in silicon determined by synchrotron white x-ray topography combined with a topo-tomographic technique. *J. Phys. D Appl. Phys.* **38**, A17 (2005).
94. Mondal, B. et al. A resistance-driven H(2) gas sensor: high-entropy alloy nanoparticles decorated 2D MoS(2). *Nanoscale* **15**, 17097–17104 (2023).
95. Pan, M. et al. A review of intelligentization system and architecture for ultra-precision machining process. *Processes* **12**, 2754 (2024).
96. Xu, K., Lyu, J. & Manoochehri, S. In situ process monitoring using acoustic emission and laser scanning techniques based on machine learning models. *J. Manuf. Process* **84**, 357–374 (2022).
97. Gaikwad, A. et al. Multi phenomena melt pool sensor data fusion for enhanced process monitoring of laser powder bed fusion additive manufacturing. *Mater. Des.* **221**, 110919 (2022).
98. Fratz, M., Seyler, T., Bertz, A. & Carl, D. Digital holography in production: an overview. *Light Adv. Manuf.* **2**, 283–295 (2021).

99. Zhao, Y., Liu, C., Zhao, Z., Tang, K. & He, D. Reinforcement learning method for machining deformation control based on meta-invariant feature space. *Vis. Comput. Ind. Biomed. Art.* **5**, 27 (2022).
100. Karkaria, V. et al. Towards a digital twin framework in additive manufacturing: machine learning and Bayesian optimization for time series process optimization. *J. Manuf. Syst.* **75**, 322–332 (2024).
101. Wang, J., Li, Y., Zhao, R. & Gao, R. X. Physics guided neural network for machining tool wear prediction. *J. Manuf. Syst.* **57**, 298–310 (2020).
102. Maier, M., Rupenyan, A., Bobst, C. & Wegener, K. Self-optimizing grinding machines using Gaussian process models and constrained Bayesian optimization. *Int. J. Adv. Manuf. Technol.* **108**, 539–552 (2020).
103. Ogoke, F. & Farimani, A. B. Thermal control of laser powder bed fusion using deep reinforcement learning. *Addit. Manuf.* **46**, 102033 (2021).
104. Lough, C. S. et al. In-situ optical emission spectroscopy of selective laser melting. *J. Manuf. Process* **53**, 336–341 (2020).
105. Sajadi, P., Rahmani Dehaghani, M., Tang, Y. & Wang, G. G. Physics-informed online learning for temperature prediction in metal AM. *Materials* **17**, 3306 (2024).
106. Goel, S. et al. Horizons of modern molecular dynamics simulation in digitalized solid freeform fabrication with advanced materials. *Mater. Today Chem.* **18**, 100356 (2020).
107. Agostinho, C. et al. Explainability as the key ingredient for AI adoption in Industry 5.0 settings. *Front. Artif. Intell.* **6**, 1264372 (2023).
108. Gross, D., Spieker, H., Gotlieb, A., Knoblauch, R. & Elmansori, M. Efficient milling quality prediction with explainable machine learning. *IFAC-PapersOnLine* **58**, 43–48 (2024).
109. Ukwaththa, J., Herath, S. & Meddage, D. A review of machine learning (ML) and explainable artificial intelligence (XAI) methods in additive manufacturing (3D Printing). *Mater. Today Comm.* **41**, 110294 (2024).
110. Xu, Z., Zhang, B., Li, D., Yip, W. S. & To, S. Digital-twin-driven intelligent tracking error compensation of ultra-precision machining. *Mech. Syst. Signal Process* **219**, 111630 (2024).
111. Zhao, R., Huang, H. & Mei, L. A method for constructing digital twins of CNC machine tools feed systems based on hybrid mechanism-data. *Sci. Rep.* **15**, 32186 (2025).
112. Stavropoulos, P., Papacharalampopoulos, A. & Athanasopoulou, L. A molecular dynamics based digital twin for ultrafast laser material removal processes. *Int. J. Adv. Manuf. Technol.* **108**, 413–426 (2020).
113. Popov, V. V. et al. Industry 4.0 and digitalisation in healthcare. *Materials* **15**, 2140 (2022).
114. Lu, J., Mu, H., Ouyang, H., Zhang, Z. & Ding, W. Modeling and effect analysis of machining parameters for surface roughness and specific energy consumption during TC18 machining using deep reinforcement learning and neural networks. *Artif. Intell. Rev.* **58**, 193 (2025).
115. Wang, P., Cui, Y., Tao, H., Xu, X. & Yang, S. Machining parameter optimization for a batch milling system using multi-task deep reinforcement learning. *J. Manuf. Syst.* **78**, 124–152 (2025).
116. Xia, C. et al. Model predictive control of layer width in wire arc additive manufacturing. *J. Manuf. Process* **58**, 179–186 (2020).
117. Wang, H. et al. Review on adaptive control of laser-directed energy deposition. *Opt. Eng.* **59**, 070901–070901 (2020).
118. Kreuzer, T., Papapetrou, P. & Zdravkovic, J. Artificial intelligence in digital twins—a systematic literature review. *Data Knowl. Eng.* **151**, 102304 (2024).
119. Sajadieh, S. M. M. & Noh, S. D. From simulation to autonomy: reviews of the integration of artificial intelligence and digital twins. *Int. J. Precis. Eng. Manuf. Green Technol.* **12**, 1–32 (2025).
120. Yeh, K.-T. & Tsai, H.-Y. Mechanically modeling chemical mechanical planarization from wafer to molecular scales: a review and discussion of future direction. *J. Mech.* **40**, 769–773 (2024).
121. Jeong, H., Kim, H., Lee, S. & Dornfeld, D. Multi-sensor monitoring system in chemical mechanical planarization (CMP) for correlations with process issues. *CIRP Ann.* **55**, 325–328 (2006).
122. Gerritsen, S. H. et al. Surface smoothing by atomic layer deposition and etching for the fabrication of nanodevices. *ACS Appl. Nano Mater.* **5**, 18116–18126 (2022).
123. Bishara, H., Lee, S., Brink, T., Ghidelli, M. & Dehm, G. Understanding grain boundary electrical resistivity in Cu: the effect of boundary structure. *ACS Nano* **15**, 16607–16615 (2021).
124. Kanarik, K. J., Tan, S. & Gottscho, R. A. Atomic layer etching: rethinking the art of etch. *J. Phys. Chem. Lett.* **9**, 4814–4821 (2018).
125. Hu, J. et al. High-sensitivity, high-throughput inspection of nanoscale defects using a laser confocal positioning-assisted darkfield imaging system. *Opt. Laser Technol.* **191**, 113269 (2025).
126. Guo, X. et al. Direct-bonded diamond membranes for heterogeneous quantum and electronic technologies. *Nat. Commun.* **15**, 8788 (2024).
127. Asadi, M., Mohseni, M,. Kashani, M. T., Fernandez, M. & Smith, M. Welding simulation integrated with machine learning to train a meta-model for fast exploration of various weld sequence scenarios, in American Society of Mechanical Engineers, vol. 6B-2019. (Pressure Vessels and Piping Division (Publication) PVP, 2019) https://doi.org/10.1115/PVP2019-93672.
128. Fujii, S. et al. All-precision-machining fabrication of ultrahigh-Q crystalline optical microresonators. *Optica* **7**, 694–701 (2020).
129. Navajas, D., Perez-Escudero, J. M., Martinez-Hernandez, M. E., Goicoechea, J. & Liberal, I. Addressing the impact of surface roughness on epsilon-near-zero silicon carbide substrates. *ACS Photonics* **10**, 3105–3114 (2023).
130. Fujii, S. et al. All-precision-machining fabrication of ultrahigh-Q crystallineÿoptical microresonators. *Optica* **7**, 694–701 (2020).
131. Arezki, Y. et al. Traceable reference full metrology chain for innovative aspheric and freeform optical surfaces accurate at the nanometer level. *Sensors* **21**, 1103 (2021).
132. Lo, W. K. et al. Enhancement of quantum coherence in solid-state qubits via interface engineering. *Nat. Commun.* **16**, 5984 (2025).
133. Kar, S. et al. Engineering of niobium surfaces through accelerated neutral atom beam technology for quantum applications. *J. Appl. Phys*. **134**, https://doi.org/10.1063/5.0153617 (2023).
134. Femi-Oyetoro, J. et al. Plasma-enhanced atomic layer deposition of titanium nitride for superconducting devices. *Appl. Phys. Lett*. **125**, https://doi.org/10.1063/5.0210190 (2024).
135. Weng, H. C. et al. Heterogeneous integration of solid-state quantum systems with a foundry photonics platform. *ACS Photonics* **10**, 3302–3309 (2023).
136. Do, N., Truong, D., Nguyen, D., Hoai, M. & Pham, C. Self-controlling photonic-on-chip networks with deep reinforcement learning. *Sci. Rep.* **11**, 23151 (2021).
137. Manjunath, M. et al. Design, fabrication and testing of reduced graphene oxide strain gauge based pressure sensor with increased sensitivity. *Microsyst. Technol.* **24**, 2969–2981 (2018).
138. Olaniyan, T., Faisal, N. & Njuguna, J. Recent developments in mechanical ultraprecision machining for nano/micro device manufacturing. *Micromachines* **15**, 1030 (2024).
139. Lin, Y.-C. *Patterned ALD Sidewall Metallization on CMOS MEMS and Applications* (Carnegie Mellon University, 2022).
140. Nawaz, H., Masood, M. U., Saleem, M. M., Iqbal, J. & Zubair, M. Surface roughness effects on electromechanical performance of RF-MEMS capacitive switches. *Microelectron. Reliab.* **104**, 113544 (2020).
141. Xu, Y., Wang, C., Lv, J., Shao, G. & Wei, X. An ultra-stable MEMS resonator with±14 ppb frequency stability realized by nonlinearity-mediated drift suppression. *Microsyst. Nanoeng.* **11**, 175 (2025).

142. Luhmann, N. et al. Effect of oxygen plasma on nanomechanical silicon nitride resonators. *Appl. Phys. Lett*. **111**, https://doi.org/10.1063/1.4989775 (2017).
143. Sakata, M. et al. Thermal conductance of silicon interfaces directly bonded by room-temperature surface activation. *Appl. Phys. Lett*. **106**, https://doi.org/10.1063/1.4913675 (2015).
144. Li, Q., Goosen, H., Van Keulen, F., Van Beek, J. & Zhang, G. Assessment of testing methodologies for thin-film vacuum MEMS packages. *Microsyst. Technol.* **15**, 161–168 (2009).
145. Dai, M. & Yan, D. Emerging flexible heterojunctions: fabrication, properties and optoelectronic applications. *Chem. Sci.* **16**, 18504–18518 (2025).
146. Jang, K.-H., Yoon, H.-S., Lee, H.-T., Kim, E. & Ahn, S.-H. 50 nm scale alignment method for hybrid manufacturing processes for full 3D structuring. *Int. J. Precis. Eng. Man.* **21**, 2407–2417 (2020).
147. Ohno, Y. et al. Chemical bonding at room temperature via surface activation to fabricate low-resistance GaAs/Si heterointerfaces. *Appl. Surf. Sci.* **525**, 146610 (2020).
148. Li, C. et al. Laser-induced adhesives with excellent adhesion enhancement and reduction capabilities for transfer printing of microchips. *Sci. Adv.* **10**, eads9226 (2024).
149. Liu, J., Wang, S. & Zhao, Q. Theoretical and experimental study on the surface microstructures of polyimide in ultra-precision fly-cutting. *Polymers* **17**, 1099 (2025).
150. Chen, S.-P., Retamal, J. R. D., Lien, D.-H., He, J.-H. & Liao, Y.-C. Inkjet-printed transparent nanowire thin film features for UV photodetectors. *RSC Adv.* **5**, 70707–70712 (2015).
151. Van Asch, J. et al. Low-loss integration of high-density polymer waveguides with silicon photonics for co-packaged optics. *Optica* **12**, 821–830 (2025).
152. Bushlya, V. et al. Performance and wear mechanisms of novel superhard diamond and boron nitride based tools in machining Al-SiCp metal matrix composite. *Wear* **376**, 152–164 (2017).
153. Iñigo, B., Colinas-Armijo, N., López de Lacalle, L. N. & Aguirre, G. Digital twin for volumetric thermal error compensation of large machine tools. *Sensors* **24**, 6196 (2024).
154. Hu, D., Grilli, N. & Yan, W. From process to property: multi-physics modeling of dislocation dynamics and microscale damage in metal additive manufacturing. *Comput. Mech.* **75**, 1241–1261 (2025).
155. Schneider, F., Das, J., Kirsch, B., Linke, B. & Aurich, J. C. Sustainability in ultra precision and micro machining: a review. *Int. J. Precis. Eng. Manuf. Green. Technol.* **6**, 601–610 (2019).
156. Singh, S., Bai, M., Matthews, A., Goel, S. & Joshi, S. N. Critical raw material-free multi-principal alloy design for a net-zero future. *Sci. Rep.* **15**, 3132 (2025).
157. Ross, N. S. et al. Performance evaluation of cutting fluids formulated with recycled toner waste and rice bran oil in sustainable machining of LMD processed Ti64 alloy. *Int. J. Precis. Eng. Manuf. Green. Technol.* **12**, 151–167 (2025).
158. Greve, G. P., Luo, C., Wu, B. & Thompson, J. K. Entanglement-enhanced matter-wave interferometry in a high-finesse cavity. *Nature* **610**, 472–477 (2022).
159. Georgi, P. et al. Metasurface interferometry toward quantum sensors. *Light Sci. Appl.* **8**, 70 (2019).
160. AAli, M., Giri, S., Yang, Q. & Liu, S. Digital twin-enabled real-time control for robot arm-based manufacturing via reinforcement learning. *J. Intell. Manuf.* https://doi.org/10.1007/s10845-025-02728-9 (2025).
161. Venkatesan, S., Cullinan, M. A. & Baldea, M. Recent advances in continuous nanomanufacturing: focus on machine learning-driven process control. *Rev. Chem. Eng.* **41**, 311–331 (2025).
162. Yin, J. -f, Bai, Q. & Zhang, B. Methods for detection of subsurface damage: a review. *Chin. J. Mech. Eng.* **31**, 41 (2018).
163. Qin, Y. et al. Micro-manufacturing: research, technology outcomes and development issues. *Int. J. Adv. Manuf. Technol.* **47**, 821–837 (2010).
164. Ikumapayi, O. M. & Laseinde, O. T. Nanomanufacturing in the 21st century: a review of advancements, applications and future prospects. *J. Eur. Syst. Autom*. **57**, https://doi.org/10.18280/jesa.570430 (2024).
165. Li, P. et al. Recent advances in focused ion beam nanofabrication for nanostructures and devices: fundamentals and applications. *Nanoscale* **13**, 1529–1565 (2021).
166. Karkaria, V., Tsai, Y.-K., Chen, Y.-P. & Chen, W. An optimization-centric review on integrating artificial intelligence and digital twin technologies in manufacturing. *Eng. Optim.* **57**, 161–207 (2025).
167. Pal, N., Ghosh, S. & Sil, R. Emerging trends in micro and nano manufacturing: a survey of modern technologies and future prospects. Mamodiya, U,. Tripathi, S. L,. Ghai, D. & Jain, D. K. (eds.) In *Enhancing Hybrid Nanodevice Fabrication Efficiency Using Machine Learning* 383–404 (John Wiley & Sons, 2026).
168. Yadavalli, V. K. The convergence of nanomanufacturing and artificial intelligence: trends and future directions. *Nanotechnology* **36**, 222001 (2025).
169. Archenti, A., Gao, W., Donmez, A., Savio, E. & Irino, N. Integrated metrology for advanced manufacturing. *CIRP Ann.* **73**, 639–665 (2024).
170. Zhou, A. et al. Research progress of hybrid bonding technology for three-dimensional integration. *Microelectron. Reliab.* **155**, 115372 (2024).
171. Yang, C. et al. Ultrafast laser-matter interaction mechanisms and applications in functional device fabrication: recent advances and perspectives. *Appl. Phys. Rev*. **12**, https://doi.org/10.1063/5.0228383 (2025).
172. Duy, T. N., Hoang Tien, D., Van Que, N. & Thi Thieu Thoa, P. Review of magnetorheological polishing techniques: advances, challenges and emerging trends. *Mater. Manuf. Process.* **41**, 1–47 (2026).
173. Fu, X., Song, H., Li, S. & Lu, Y. Digital twin technology in modern machining: a comprehensive review of research on machining errors. *J. Manuf. Syst.* **79**, 134–161 (2025).

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The authors declare no competing interests.

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