

Nanofabrication: Advances, Applications, and Future Prospects In Emerging Technologies

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Nanofabrication has emerged as a transformative discipline, providing precise control over materials at atomic and molecular scales, which has resulted in substantial advancements across various industries. This review examines the fundamental principles, key techniques, and applications of nanofabrication, emphasizing top-down techniques (such as photolithography, electron beam lithography, and focused ion beam milling) and bottom-up methods (such as molecular self-assembly, chemical vapor deposition, and atomic layer deposition). The influence of nanofabrication is particularly notable in sectors such as semiconductor technology, biomedical applications, energy storage solutions, environmental remediation, aerospace engineering, and quantum computing. Despite these remarkable achievements, challenges remain, including high fabrication costs, scalability limitations, and environmental implications. Future research initiatives are anticipated to concentrate on sustainable nanomanufacturing practices, artificial intelligence-driven process optimization, and integration of nanotechnology with emerging fields as quantum computing and biomedicine. With ongoing innovations, nanofabrication is poised to revolutionize next-generation materials and technologies, thereby driving significant scientific and industrial advancements in the twenty-first century. Word 97-2003

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Nanofabrication is the process of designing, synthesizing, and manipulating materials and structures at the nanoscale (10⁹ m), usually within the size range of 1–100 nm. Precise control over the dimension, morphology and composition of the materials is required to yield functional devices with unique physical, chemical, and electronic.¹ Nanofabrication is

generally divided into two main approaches: top-down fabrication, which involves the removal of nano-sized materials and structures using methods such as lithography and etching, and bottom-up fabrication, in which nanoscale structures are built from the ground-up through chemical and physical processes, such as self-assembly and molecular synthesis.² Nanofabrication plays an

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indispensable role in modern technology as it not only makes ever smaller, faster and more efficient devices, but also imparts new functionalities. Nanofabrication is essential to the electronics and semiconductor industry by allowing the production of smaller transistors, resulting in the production of microprocessors and memory storage that store close to a billion transistors, while being high-speed and low-energy.³

They have also played a role in advances in quantum computing, where nanoscale structuring precision is crucial for the creation of quantum circuits. In the biomedical domain, nanofabrication has revolutionized drug delivery approaches, enabling targeted therapies using nanoscale carriers. Additionally, nanometer-scale biosensors offer extremely sensitive methods for disease detection, and nanomaterials are being investigated for use in tissue engineering and regenerative medicine.⁴ Nanofabrication greatly impacts the energy and environmental sciences, paving the way for the development of high-efficiency solar cells, novel nanomaterials for batteries and supercapacitors, and emerging technologies for water purification.⁵ Nanofabrication methods have aided the progress of photonics and optoelectronics with applications in high-performance light-emitting diodes (LEDs), photodetectors, and plasmonic nanostructures that augment light-matter interaction.⁶ In addition, nanoscale sensors are increasingly used in a number of industries, such as aerospace and automobile for gas detection, monitoring structural integrity, and improving autonomous systems.⁷

The precursor ideas of nanofabrication were laid out in physicist Richard Feynman's famous 1959 lecture, "There's Plenty of Room at the Bottom," in which he described the implications of manipulating atoms and molecules to create nanoscale structures.⁸ Nonetheless, real progress in nanofabrication began with photolithography in the 1970s, which allowed for the fabrication of microelectronics and paved the way for the semiconductor industry. Ongoing pressure for miniaturization has resulted in the development of electron beam lithography and atomic force microscopy (AFM) has enabled researchers to begin imaging and manipulating individual atoms, ushering in the age of nanotechnology.² The introduction of bottom-up approaches (like self-assembly and molecular beam epitaxy

(MBE)) during the 1990s transformed the field of nanofabrication, enabling the assembly of nanostructures from atomic-level building blocks.¹⁰ These new carbon nanomaterials are classified under the term nanofabrication with the arrival of fullerenes, carbon nanotubes, and later graphene, leading the exploration of new polymers with unique mechanical, electrical, and optical properties. Nanoimprint lithography (NIL) and atomic layer deposition (ALD) emerged in the 2000s as low-cost and scalable processes for creating nanoscale features with high fidelity. Biological nanofabrication technologies, including DNA origami and protein-based nanostructures, have opened the door to innovative applications in the biomedical field.¹¹

At present, a new level of exploration and progress is being made with nanofabrication through the introduction and integration of artificial intelligence, machine learning and sophisticated computational modelling. These advancements have significantly improved the accuracy and effectiveness of nanoscale production methods.¹² Diverse recent methodologies, including two-photon lithography, three-dimensional nano printing, and quantum dot fabrication, have catalyzed the evolution of next-generation nanodevices across disciplines, including quantum computing and nanomedicine.¹³ As continuously growing innovation and interdisciplinary synergy continue to propel the field, nanofabrication is expected to revolutionize a variety of industries by enabling the design and development of ultra-small, high-performance materials and devices that will define the future of technology and science.¹⁴

The following overview describes a range of nanofabrication techniques, their historical progression, and the importance of nanostructured materials for multiple scientific and industrial fields. To discuss these topics, we provide a summary of the basics of nanofabrication followed by a brief overview of the different techniques available along with their advantages and challenges. This is significant because it explores not only established methodologies, such as photolithography, electron beam lithography and focused ion beam milling, but also up-and-coming techniques that include bottom-up processes such as self-assembly, chemical vapor deposition and atomic layer deposition. This review

highlights the importance of nanofabrication in transforming fundamental sectors like electronics, healthcare, energy, photonics, and environmental science. Moreover, it addresses recent developments, existing challenges, and potential future trends in this field. It is hoped that researchers, engineers, and industry professionals from diverse backgrounds will come away with a comprehensive understanding of the current trends in nanofabrication, near-term limitations, and implications for future breakthrough developments. This review aims to advance the current trends in nanoscale technologies and stimulate new research directions for materials and devices by systematically reviewing the existing state of the art fabrication methodologies and applications.

Fundamentals of nanofabrication

Nanotechnology is based on the fact that nanoscale materials have unique physical, chemical, and biological properties that differ greatly from their nanoscale forms. The unique properties of these materials at the atomic and molecular levels, including their high surface-to-volume ratio, quantum confinement, and increased reactivity, manifest as nanoscale phenomena.¹⁵

Nanofabrication A primary component of nanotechnology is its ability to fabricate and assemble structures in the nanometer size range in a controllable way to make functional nanodevices and nanosystems.

Nanofabrication involves two main techniques top-down, and bottom-up, which are based on different principles. Top-down approaches such as photolithography and electron beam lithography etch massive materials and generate nanoscale structures using interactions with optical and electron beams. In contrast to top-down approaches, bottom-up approaches such as self-assembly and chemical vapor deposition mathematically construct three-dimensional structures from atoms or molecules using intermolecular interactions and controlled chemical reactions.¹⁶ These fabrication techniques are governed by nanoscale precision, defect minimization, and material property control. An understanding of the key principles behind the fields of nanotechnology and nanofabrication is also crucial for the design of new nanoscale materials and devices with enhanced functions in

a range of fields, including electronics, medicine, energy, and environmental applications.

Nanoscale materials and structures

Nanoscale materials and structures refer to materials or structures with at least one dimension within the 1–100 nm range, showing an intriguing suite of mechanical, electrical, optical, and chemical properties that are remarkably different from those of their bulk materials. These materials are in the form of nanoparticles, nanowires, nanotubes, quantum dots and thin films, exhibiting specific properties and several applications.¹⁷ Nanomaterials such as those based on carbon like graphene and carbon nanotubes (CNTs), have the well-known properties of extreme strength, high electrical conductivity and extreme flexibility. Such properties render them uniquely conducive for further developments in electronics, energy storage systems, and exciting biomedical applications. Moreover, metal and semiconductor nanoparticles, such as treasured gold and silver nanoparticles, are important molecules for use in catalysis, drug delivery and sensing technologies. These materials have tunable optical and surface properties, enabling applications tailored to specific scientific and industrial needs.¹⁸

These semiconductor nanocrystals also exhibit compelling size-dependent optical properties and are particularly then important in state-of-the-art imaging and display technologies. Quantum nanocrystals have also enabled the development of vortex beam with tailored morphologies for customized and high-resolution visual displays. Nanostructured thin films and coatings also add advanced functionalities to surfaces, such as anti-reflective, anti-corrosive, and antimicrobial properties. Nanofabrication techniques represent the precise engineering of nanoscale materials and structures for industrial use, leading to a paradigm shift in numerous industries.¹⁹ The ability to control matter at the atomic level has enabled the development of advanced materials that push the boundaries of what is possible in next-generation applications.

Scaling laws, surface-to-volume ratio, quantum effects

This is because, nanoscale materials have different properties than their bulk counterparts and nanotechnology is built upon the foundational

laws that determine these differences. These laws, surface-to-volume ratios, and quantum effects are some of these principles. Scaling laws govern the evolution of material properties as the material is reduced to nanoscale. In some instances, the mechanical strength is enhanced, however, the thermal and electrical conductivities depend on various atomic interactions.²⁰ Going down to nanoparticles, the surface-to-volume ratio, the fraction of the total number of atoms that are on the surface, becomes the crucial factor. This exposure significantly increases the reactivity, catalytic activity and interactions with the environment. This property is of particular significance for drug delivery, catalysis, and sensors that involve surface interactions. As we scale down to a few nanometers, quantum effects, such as tunnelling, dominate when interacting with these nanostructures. One of these phenomena is quantum confinement, where the behavior of electrons is restricted to small dimensions, resulting in alterations in the electrical, optical, and magnetic properties.²¹ This effect forms the foundation for quantum dots (which have an intensity dependent on size), and nanoscale transistors that improve the performance of electronic devices.

Techniques in nanofabrication

Top-Down Approaches

Another nanofabrication principle, the top-down approach, is based on the careful patterning and etching of bulk materials to create an atomically precise nanoscale architecture. An example of this approach has been utilized in semiconductor technology for over 40 years. Top-down nanofabrication is another prominent approach in semiconductor technology, but it is also used in nanodevice manufacturing and precision material processing. Unlike constructional principles of bottom-up nanofabrication, which starts with a bulk material and constructs a nanostructure atom by atom or molecule by molecule, top-down nanofabrication starts with the bulk material, and through subtractive methods carves the material in the desired nanoscale geometry. The main methods of top-down nanofabrication are photolithography, electron beam lithography, focused ion beam milling, and several etching methods, such as reactive ion etching and wet chemical etching.^{22,23}

Photolithography

Top-down approaches to nanofabrication such as photolithography are among the most commonly applied and, have been widely employed in semiconductor manufacturing, microelectronics, and Microelectromechanical Systems (MEMS). Dillinger is a photolithographic technique that transfers a pattern onto a substrate using a photoresist.²⁴ It starts with a silicon disk called a wafer which is covered with a very thin layer of photoresist. Next, a photomask containing the desired pattern is placed over the wafer, and ultraviolet (UV) light is projected onto the surface. When exposed to light, chemical changes occur in the photoresist that either makes the exposed areas more soluble (for positive resists) or less soluble (for negative resists) in a developer solution. This leads to selective removal of the photoresist and exposes some areas of the underlying substrate. This exposed material is altered in various ways by subsequent etching or deposition processes to produce nanoscale features with very high precision.²⁵ The inclusion of photolithography in the VLSI process has made the batch production of integrated circuits (ICs) and nanodevices, possible because of its scalability, exactness and capacity to deliver intricate patterns. However, its resolution is restricted by the wavelength of the incident light, which is on the order of ~193 nm for conventional deep ultraviolet (DUV) lithography. To overcome this limitation, extreme ultraviolet (EUV) lithography (with a wavelength of 13.5 nm), which enables feature sizes below 10 nm, has been successfully developed. Nanopatterning with ultra-high resolution can be achieved using other techniques such as nanoimprint lithography and electron beam lithography (EBL) in combination with photolithography. However, photolithography is a pillar of nanofabrication because of its potential to fabricate complex geometries over large areas, thereby enabling advancements in microchips, nanophotonics, and new computing architectures.²⁶

EBL (electron beam lithography)

EBL is an advanced patterning technique used in nanofabrication to create very small, sub-10 nm features. In contrast to traditional photolithography, which uses ultraviolet light and photomasks, EBL utilizes a tightly focused and,

finely controlled beam of electrons to directly write complex features to an electron-sensitive resist material such as polymethyl methacrylate (PMMA).²⁷ When exposed to this electron beam, the resist changes its solubility in a way that allows the selective removal of the material in a later development step. This revolutionary method provides unprecedented accuracy and flexibility, making it ideal for research projects, prototype development, and applications requiring nanometric features including quantum computing, plasmonics and nanophotonics.²⁸

Although incredibly powerful, EBL has limitations, especially in terms of throughput and cost efficiency. Similar to photolithography, this process patterns features one at a time, which is why it is much slower and for that reason not practical for mass production. Additionally, electron scattering may inadvertently expose areas that are not meant to be present, contributing to pattern blurring due to the proximity effect. These failure rates have challenged researchers to develop advanced correction algorithms and multiple pass exposures that increase the fidelity of the fabricated patterns. Although EBL is not a mainstream method for semiconductor fabrication, it is a crucial tool for producing nanoscale devices and masks and facilitates pioneering work on new nanotechnologies.²⁶

Nanoimprint lithography (NIL)

Nanoimprint Lithography (NIL) is recognized as an innovative technique that provides replication of nanoscale structures with high accuracy and at low cost. NIL employs mechanical patterning as opposed to the optical or beam-based exposure used to transfer patterns in traditional lithographic techniques such as photolithography and electron beam lithography (EBL), allowing for the direct dicing of a pre-defined template into a resist-coated substrate. Here we exploit direct contact to remove the diffraction limits associated with optical lithography and achieve an accurate copy transfer down to extremely small features, with the resolutions of less than 10 nm at times.²⁹ At the beginning of the NIL process, a stamp with nanoscale features to be transferred was imprinted. Usually formed of materials such as silicon, quartz or metal, this mold is pressed against a thin layer of polymer resist under very well-controlled temperature and pressure conditions. NIL can also

be divided into thermal NIL, where the resist is heated to be soft during imprinting, and UV NIL, where a liquid resist is molded and then cured by ultraviolet light, depending on the type of resist used. After the imprinting process, the imprint template is removed from the structure, leaving only the replicated pattern behind for further etching, deposition, or any post-processing steps to improve the features and develop them into functional devices.²⁴

One of the highest resolutions of NIL prepared by this method provides the fabrication of nanoscale features that outclass the capability of photolithography (conventional). Because NIL is independent of light sources or electron beams, it is not limited by the resolution limits related to the wavelength, thus making it a strong candidate for ultra-high precision patterning.³⁰ Second, NIL has high throughput owing to the replication of numerous nanoscale patterns in a single imprinting process. This characteristic makes it especially suitable for mass production applications such as semiconductor fabrication, photonic components, nanophotonics, and microfluidic devices.³¹ Furthermore, NIL is compatible with a variety of materials (polymers, metals, oxides, and biological substrates), which can be applied in various fields such as nanoelectronics, flexible electronics, and biomedical devices. In Addition, NIL is a cost-effective solution for the implementation of high-end photolithography because of its reliance on expensive optical components and templates, making it a suitable candidate for cutting-edge nanoscale technologies.³¹

Despite the many advantages, NIL faces issues that need to be resolved for wide acceptance in the semiconductor and nanofabrication industries. A concern at this stage is also the sustainability of the stamp, where imprinting numerous times will result in abrasion and contamination forces that may alter the mark over time. Another challenge lies in the precision of alignment, especially in creating multi-layered nanoscale structures where even slight misalignments can introduce defects in intricate integrated circuits.³² Additionally, defects in the resist adhesion and trapped air bubbles during the imprinting process may also introduce defects in the final pattern, influencing the overall quality and yield. To overcome these obstacles, scientists are currently working to establish high-precision

imprinting techniques, self-cleaning templates, and automated alignment systems to improve reproducibility and reliability. As materials science, nanofabrication methodologies, and hybrid lithographic techniques continue to evolve, NIL is poised to be an integral player in the future low-cost, high-resolution nanomanufacturing landscape.³² Their potential uses range from conventional electronics to wearable sensors, flexible displays, next-generation optical systems, and biomedical nanotechnology, where high-throughput, high-quality, low-cost nanoscale patterning is essential. It is expected that with the aid of progressing NIL technology and its limitations, NIL will change the world through a widely applicable, inexpensive, and optimized method of generating 3D manufacturing of new nanodevices.

FIB = focused ion beam FIB milling

Focused Ion Beam³³. While standard etching techniques are limited by the complexities of mask lithography, FIB milling is a direct-write process that enables fabrication of complex nanostructures, targeted treatments, and preparation of high-resolution cross-sections for thorough material characterization.³⁴

This approach is performed when they accelerate a beam of gallium ions shot into a target material, where collisions with the ions produce sputtering that removes a layer of material. Research can achieve sufficiently detailed fabrication of nanostructures with feature sizes limited to a few nanometers by controlling parameters like ion dose, beam energy, and milling pattern. This ability to locally modify the material, without necessitating the use of masks or resist layers, along with the various beam species FIBs operate with makes it a common technique for semiconductor device fabrication/failure analysis, as well as providing a rapid prototyping platform for nanostructures. Interlayer distance control is of particular importance for preparation of samples for transmission electron microscopy (TEM), where imaging typically requires atomic thicknesses.³⁵ Furthermore, FIBs are typically paired in a dual-beam system with scanning electron microscopes (SEMs) allowing for real-time correlative imaging and milling. The approach is not without its disadvantages though, such as slower processing rates than might be expected because of the

serial nature of the process, destruction of delicate material through ion implantation and undesired redeposition of sputtered material on neighbouring surfaces. The implementation of cryogenic, low-energy ion milling, and gas-assisted etching to improve the efficiency and prevent the sample's radiation damage in the sample addresses some of these limitations. FIB, fueled by continuous developments in the functionality of ion sources, ion beam manipulation, and multi-ion milling strategies, appears to be a competitive and miniaturized platform for advanced nanofabrication, imperfections characterization, and 3D nanostructures fabrication, particularly in nanoelectronics, plasmonics and biomaterials.^{28,36} Its capacity for highly localized transformations makes it a potent avenue for new nanodevices and material properties at the atomic limit.

Bottom-up approaches

Chemical Vapor Deposition (CVD) is an advanced and commonly utilized nanofabrication method that allows the precise deposition of thin films or complex nanoscale structures onto a substrate via controlled chemical reactions between gaseous precursors. This flexible technique is crucial for semiconductor fabrication, thin film coating and advanced nanomaterial synthesis including carbon nanotubes and graphene.⁴⁴ The process of CVD begins with the introduction of selected precursor gases into the reaction chamber. These gases undergo thermal decomposition or chemical reactions on the heated substrate, leading to the formation of a solid material. At the same time, any volatile byproducts are cleanly removed from the system. A key advantage of CVD technology is its superior ability to manipulate multiple parameters such as the film thickness, the material composition, and its crystallinity.⁴⁵ Due to its extreme level of precision, it is therefore ideally suited for more advanced nanotechnology applications. Many CVD techniques have found adaptation for specialized materials and device applications including, Low-Pressure CVD (LPCVD), Plasma-Enhanced CVD (PECVD), and Metal-Organic CVD (MOCVD). CVD is a widely applicable process employed in nanoelectronics to deposit not only dielectric layers, but conductive ones as well, making it essential in manufacturing ultra-modern electronic elements. Furthermore, CVD is also instrumental to the fabrication of

Table 1. Nanoscale materials and their significant properties, structures, and uses

Type of Nanoscale Material	Structure	Key Properties	Applications
Nanoparticles	Spherical or irregular nanostructures (1–100 nm)	High surface area, quantum size effects, tunable optical properties	Drug delivery, catalysis, biosensors, imaging, coatings
Nanowires	One-dimensional structures with high aspect ratio	High electrical and thermal conductivity, mechanical flexibility	Nanoelectronics, sensors, energy harvesting (solar cells, batteries)
Carbon Nanotubes (CNTs)	Cylindrical graphene structures (single-walled or multi-walled)	Exceptional strength, high electrical and thermal conductivity	Electronics, composite materials, drug delivery, structural reinforcement
Graphene	Two-dimensional, single layer of carbon atoms	High electrical conductivity, mechanical strength, flexibility	Flexible electronics, batteries, supercapacitors, sensors
Quantum Dots	Semiconductor nanocrystals (2–10 nm)	Size-dependent optical properties, fluorescence, high photostability	Bioimaging, display technology (QLEDs), photovoltaics
Nanocomposites	Hybrid materials with nanoscale reinforcements	Enhanced mechanical, thermal, and barrier properties	Aerospace, automotive, packaging, structural materials
Nanostructured Thin Films	Ultra-thin layers of nanomaterials	Optical transparency, high surface functionality, protective coatings	Antireflective coatings, corrosion resistance, antimicrobial surfaces

Table 2. Scientific Evidence and Applications of Top-Down Nanofabrication Techniques

Nanofabrication Technique	Principle	Resolution Limit	Key Applications	Scientific Evidence & Examples
Photolithography	Uses light to transfer a pattern from a mask to a photoresist on the substrate.	Down to ~12 nm with EUV Lithography	Semiconductor manufacturing, microchip fabrication, photomask production	Recent advances in photolithography enable vertically aligned nanowires for photonics ³⁷ and improved artificial vision devices. ³⁸ Flexible and stretchable sensors have been developed using photolithography. ³⁹
Electron Beam Lithography (EBL)	Uses a focused electron beam to directly write nanoscale patterns on resist-coated substrates.	Sub-10 nm feature size	Semiconductor prototyping, high-resolution device fabrication, nanotech research	Improved process control helps EBL address challenges in silicon nanostructures ⁴⁰ and enables quantum dot patterning. ⁴¹
Nanoimprint Lithography (NIL)	Mechanical molding technique where a patterned mold physically imprints nanoscale features into a resist.	Sub-10 nm	Integrated circuit production, photonics, biotechnology, memory devices	NIL-compatible high refractive index optical materials have been developed for photonics. ⁴² NIL combined with laser ablation offers new surface engineering methods.
Focused Ion Beam (FIB) Milling	Uses a focused ion beam to sputter/mill material from a substrate for patterning or cross-sectioning.	~5 nm	Micro/nanofabrication, device prototyping, materials characterization	FIB used for 2D and 3D photonic structures and plasmonic device fabrication with high precision. ⁴³

Table 3. Scientific Evidence and Examples of Bottom-Up Nanofabrication Techniques

Nanofabrication Technique	Principle	Resolution Limit	Key Applications	Scientific Evidence & Examples
Self-assembly (DNA Origami, Block Copolymer Lithography)	Molecular components spontaneously organize via programmable interactions (e.g., base pairing, block copolymer microphase separation).	~5-10 nm (DNA Origami sub-10 nm; BCP sub-10 nm features reported)	Nanoscale biosensors, drug delivery, nanomachines, nanoscale patterning, advanced lithography	DNA Origami enables precise 2D and 3D nanostructures for biosensing and nanofabrication. ⁵²⁻⁵⁴ Block copolymer lithography achieves sub-10 nm patterning by directed self-assembly of chemically tailored copolymers. ⁴⁹
Chemical Vapor Deposition (CVD)	Thermal decomposition or phase precursors to form thin solid films on substrates.	Few nm thickness control, feature resolution limited by mask or precursor diffusion	Semiconductor devices, nanoporous coatings, mechanical strengthening of composites	Used for nanoporous coatings and thin films enhancing mechanical and antimicrobial properties. ⁵⁵
Atomic Layer Deposition (ALD)	Sequential, self-limiting surface reactions deposit uniform atomic-thin layers with atomic scale thickness control.	Atomic-scale (~1-3 Å layer thickness)	Semiconductor electronics, catalysts, MEMS, sensors, optics	ALD provides conformal coatings with precise atomic thickness control for semiconductor fabrication. ⁵¹
Molecular Beam Epitaxy (MBE)	Molecular or atomic beams deposited under ultra-high vacuum to grow epitaxial thin films layer-by-layer.	Sub-nanometer; atomic-level control	Epitaxial films for quantum devices, optoelectronics, novel materials	In situ MBE characterization techniques aid precise growth control of epitaxial films for quantum electronics. ⁵⁶
Sol-Gel Processing	Hydrolysis and polycondensation of molecular precursors form a "sol" transitioning into a "gel" and then solid material.	Nanometer scale control, ~1-100 nm particle size	Nanoparticles synthesis, bioactive glasses, catalytic and drug delivery coatings	Enables controlled synthesis of nanoparticles and bioactive materials by sol-gel chemistry. ⁵⁷
Electrochemical Deposition	Metal ions reduced and deposited on a conductive substrate by applied electric current.	Nanoparticles and films down to a few nm	Nanostructured electrodes, catalysis, sensors, shape-controlled nanoparticles	Electrochemical deposition allows catalytic nanoparticle synthesis with controlled morphology. ⁵⁸
Colloidal Synthesis	Formation of nanoparticles by nucleation and growth in solution with ligand control for size and shape tunability.	Typically 1-100 nm; shape and size tunable	Quantum dots, metal nanoparticles for catalysis, sensors, biomedical applications	Ligand engineering and time-resolved studies elucidate nucleation and stability in colloidal nanoparticles. ⁵⁷

Table 4. Applications of Nanofabrication

Application Area	Key Technologies	Major Advancements	Examples
Electronics & Semiconductors	Photolithography, Electron Beam Lithography (EBL), Extreme Ultraviolet Lithography (EUV)	Miniaturized transistors, high-density integrated circuits, flexible electronics	Advanced microprocessors, quantum dot transistors, flexible OLED displays
Biomedical & Healthcare	Nanoparticle drug delivery, Lab-on-a-chip, Biosensors, Tissue engineering	Targeted drug delivery, early disease detection, regenerative medicine	Liposomal drug formulations, glucose biosensors, nano-scaffolds for tissue regeneration
Energy Storage & Conversion	Nanostructured batteries, Supercapacitors, Thin-film solar cells, Fuel cells	Higher energy density, fast charging, improved efficiency in renewables	Lithium-ion batteries, Perovskite solar cells, Hydrogen fuel cells
Optoelectronics & Photonics	Quantum dots, Plasmonic nanostructures, Photonic crystals	High-resolution displays, optical data transmission, enhanced imaging	LED screens, Laser diodes, Optical sensors
Environmental Applications	Nanomembranes, Catalytic nanomaterials, Nanosensors	Water purification, carbon capture, real-time pollution monitoring	Nanofiltration systems, Smart air quality sensors, Carbon nanotube-based filters
Aerospace & Manufacturing	Nanostructured coatings, Lightweight nanocomposites, 3D nanoprinting	High strength-to-weight ratio, improved fuel efficiency, durability	Carbon-fiber reinforced aircraft materials, Corrosion-resistant coatings, Precision-engineered microstructures
Quantum Computing & Advanced Materials	Quantum dots, Superconducting qubits, 2D nanomaterials	Next-generation computing, enhanced conductivity, novel materials	Graphene-based transistors, Topological insulators, Qubit-based quantum processors

advanced thin-film solar cells and high-performance battery electrodes in energy applications. The ability of CVD to create pure, uniform, and conformal coatings has made it a foundational approach in the arenas of nanofabrication and materials engineering, advancing innovation in a wide spectrum of technology sectors.

Molecular beam epitaxy (MBE)

Molecular Beam Epitaxy (MBE) is a premier form of nanofabrication to accurately deposit thin films and epitaxial layers down to the atomic level. It is widely used in semiconductor industry and nanotechnology fields for the fabrication of high-purity and high-performance electronic and optoelectronic devices. MBE is an ultra-high vacuum (UHV) process in which highly purified elemental or molecular beams impinge on a pedestal substrate that is heated. The substrate surface then condenses these beams forming epitaxial layers with highest structural quality.⁴⁶ Unlike chemical vapor deposition (CVD), which relies on gas-phase reactions, MBE utilizes physical deposition mechanisms, allowing for greater control of composition and thickness at the atomic level. One of the key benefits of MBE is its ability to grow by the layer which makes it particularly applicable to the development of heterostructures, quantum wells, and superlattices with well-defined interfaces. This method performs a critical role in the synthesis of semiconductor devices like high-electron-mobility transistors (HEMTs), infrared sensors, and laser diodes.⁴⁷ In addition, MBE allows in-situ observation of film growth via RHEED, which leads to the real-time optimization of the fabrication process. MBE is recognized as a slow and expensive technique with excellent precision. Therefore, it is suitable for research purposes and high-quality projects, not industrial mass production. Nonetheless, its unique ability to synthesize complex nanostructures and next-generation electronic materials is making it ever more a mainstay in the toolbox of nanotechnology and semiconductor fabrication.⁴⁸

Self-assembly methods (e.g., DNA origami, block copolymer lithography)

Self-Assembly Techniques for Nanofabrication

Self-Assembly, a phenomenal bottom-up nanofabrication method, refers to the natural organization of molecules or nanoscale units into specific structures, as determined by intermolecular

interactions. Self-assembly promotes the development of higher order nanostructures with little external influence, as observed in classic top-down approaches such as photolithography. Molecules are driven to self-assemble by a number of fundamental forces, including van der Waals interactions, hydrogen bonding, electrostatic forces, and hydrophobic interaction. Read more: Forces at the nanoscale enable the assembly of functional architectures, self-assembly methods, including DNA origami and block copolymer lithography are common.⁴⁸

DNA Origami

DNA origami is a promising technique for molecular self-assembly allowing us to utilize the programmability of DNA base pairing to make, very complex nanoscale structures with astonishing precision. In this new approach, they can use long single-stranded DNA “scaffolds” and wrap them with shorter complementary “staple” strands to create the desired shapes and form complex 2D and 3D nanostructures. The ability to create very precise and functional nanoscale patterns has propelled the use of DNA origami across various fields, from drug delivery and biosensing to molecular computing and nanorobotics. This is partly because researchers have successfully employed DNA origami for the organized assembly of various nanoparticles, proteins, and other biomolecules in a controllable manner, and has expanded promise of nanoelectronics and biomedicine.¹¹

Block Copolymer Lithography

Block copolymer (BCP) lithography has become a widely adopted example of a self-assembly based nanofabrication technology that, utilizes bulk or thin film phase separation from diblock or triblock copolymers to create 3D periodic and uniformly highly homogenous nanoscale patterns. Due to thermodynamic incompatibility, block copolymers comprise two or more chemically different polymer segments that spontaneously separate into well-defined morphologies (spheres, cylinders, or lamellae). The nanostructures can be transferred to substrates and used in nanoelectronics, membrane technology, and nanophotonics and can be produced by carefully controlling the polymer composition, molecular weight, and polymer processing conditions to obtain highly ordered nanopatterns. BCP lithography is known to be a more cost effective

method than the traditional lithography techniques, especially appropriate for sub-10 nanometer feature fabrication, and is extremely interesting for use in the semiconductor industry and next-generation data storage.⁴⁹

Atomic layer deposition (ALD)

Atomic Layer Deposition (ALD) is an extremely advanced thin-film technique that allows the precise atomic-scale growth of materials. By a sequence of vapor phase precursors exerting self-limiting surface reactions (unlike chemical vapor deposition (CVD), where the gaseous precursors react continuously in a thermodynamically controlled environment), this method enables the deposition of thin films evenly and uniformly, even onto complex three-dimensional architectures. ALD use a stepwise approach of exposing a singular atomic layer of precursor gas in each step. After the cycle has completed, this process is repeated iteratively to deposit precise film thickness. ALD technology is used in the semiconductor industry for challenging depositions such as high-k dielectric layers such as hafnium oxide (HfO₂) and aluminum oxide (Al₂O₃) which are both deposited over the channel and gate in transistors and memory devices application.⁵⁰ This has made it even more relevant due to its ability to produce pinhole free high-purity films within applications of nanoelectronics, energy storage, biomedical coatings and protective layers for sensors. ALD is also conducted at low temperatures, making it compatible with temperature-sensitive substrates. Thanks to its atomic-scale precision, good step coverage, and capability to produce high-quality films, ALD has been an important nanofabrication and materials science technique.⁵¹

Applications of nanofabrication

As such, nanofabrication has rapidly become a disruptive technology that has won the market across multiple industries because it allows for precision-based manipulation of materials and their structures at the atomic and molecular levels. This has resulted in major progress in electronics, healthcare, energy, environmental sciences, aerospace, and quantum computing. Nanofabrication technologies like extreme ultraviolet (EUV) lithography and atomic layer deposition (ALD) in the electronics and semiconductor industry have enabled the production of ultra-small transistors, high-

density integrated circuits (ICs), and memory devices. These innovations not only accelerated computational speed and energy efficiency but also facilitate the miniaturization of electronic elements, leading to more powerful and smaller devices such as smartphones, high-performance computers, and artificial intelligence (AI) processors. Additionally, the incorporation of nanomaterials, including graphene and carbon nanotubes, has enabled advancements in flexible and wearable electronics due to their increased mechanical strength, conductivity, and durability.⁵²

In biomedical and healthcare field, nanofabrication is critical for the fabrication of advanced drug delivery systems, biosensors and tissue engineering scaffolds. Liposomes, dendrimers, polymeric nanoparticles, and other nano drug carriers enable the targeted delivery of drug that limit side effects, which can improve the therapeutic efficacy. For example, there are nanoparticle-based cancer therapies that deliver drugs directly to tumor cells and reduce interaction with healthy tissues. For example, high sensitivity and specificity of nanofabricated biosensors such as glucose sensors for diabetes management devices and lab-on-a-chip devices for rapid disease diagnostics. Nanostructured coatings and scaffolds have been used in regenerative medicine and organ transplantation, to enhance cell adhesion, proliferation and differentiation. Nanofabrication has been a key enabler for the development of energy storage and conversion technologies in the energetics sector.⁶⁰ Nanostructured materials increase the energy density and speed of charge-discharge cycles of a lithium-ion battery, supercapacitor, and hydrogen fuel cells as a result of the enormous surface area and electrical conductivity. This progress consists of thin-film solar cells, quantum dot photovoltaics, and perovskite nanomaterials development that increased solar energy conversion effectiveness so it is able to accomplish renewable sources of energy more attainable and cheaper. Moreover, as per the sustainable processes clean energy wires have been used in processes such as hydrogen process and carbon capture technologies which are used in the production of catalytic nanomaterials.⁶¹

Advanced nanofabrication allows for the realization of high-performance optoelectronic devices, such as light-emitting diodes (LEDs),

laser diodes, and photonic crystals. These advances improve optics for communication, imaging technologies (e.g., ROS with super-resolution), and high-resolution display systems. The enhanced light-matter interactions exhibited by plasmonic nanostructures, which are integrated into sensors, are invaluable for medical diagnostics and environmental monitoring.⁶² Additionally, nanoscale optical waveguides play an important role in fiber-optics networks, where they transmit data at very high speeds and with better reliability.

Nanofabrication plays a role in Environmental applications which offers promise in areas like pollution control, water purification and sustainable waste management. Moreover, they are very efficient for filtering the contaminants, heavy metals, and pathogens from water source, leading to clean and potable water for the people. Such nanosensors can be embedded in smart monitoring systems to monitor real-time air pollutants, toxic chemical emission and environmental threats for proactive environmental management. Moreover, catalytic nanomaterials play a vital role in carbon capture, reducing the release of greenhouse gases and mitigating climate change. In high-end manufacturing areas, nanostructured coatings and nanocomposites can provide high strength, corrosion resistance and high-temperature stability for aircraft, spacecraft and other aerospace-related materials. These materials reflect improved fuel efficiency with decreased wear extending the lifespan of aerospace components.⁶³ In particular, the advanced applications of 3D nanoprining allow the precise fabrication of complex microstructures used in multiple industry domains (e.g., robotics, sensors, and microfluidic devices).

Nanofabrication is also creating new avenues in quantum computing and next-generation materials. Quantum dots, superconducting qubits, and topological insulators created on a nanoscale are all foundational for quantum computers, expected to outpace classical computers exponentially for applications in cryptography, artificial intelligence, and complex simulations. The identification and development of new nanoscale materials (e.g. graphene, MoS₂, 2-dimensional) have created unprecedented opportunities in the areas of electronics, photonics and energy storage.⁶⁴

The development of nanofabrication techniques provides such capabilities, and they

are likely to induce major advancements in diverse domains, meeting some of the most severe global challenges. This capacity to design materials with extraordinary precision at the nanoscale will give rise to smarter, more energy-efficient, and more sustainable technologies which will define the next era of science and industry.

Challenges and Future Directions

Nanofabrication has transformed various industries by allowing precise control over materials at the nanoscale level. This has led to groundbreaking advancements in the fields of electronics, healthcare, energy, environmental science, aerospace, and quantum computing. Techniques such as photolithography, electron beam lithography, molecular self-assembly, and atomic layer deposition have facilitated the development of high-performance semiconductor devices, targeted drug delivery systems, efficient energy storage solutions, and next-generation materials. These innovations have not only enhanced existing technologies but have also opened doors to entirely new fields, including quantum computing and molecular-scale electronics.⁶⁵ Despite these significant advancements, nanofabrication still faces challenges, including high production costs, scalability issues, and the need for more environmentally friendly synthesis methods. The complexity of nanoscale processes necessitates ongoing research on more precise, cost-effective, and sustainable fabrication techniques. The future of nanofabrication lies in integrating artificial intelligence (AI) and machine learning for process optimization, utilizing advanced 3D nano printing for creating complex nanostructures and developing self-assembling nanomaterials that can autonomously organize into functional devices. Additionally, biocompatible nanofabrication techniques will enhance applications in regenerative medicine and biomedical engineering.²² Looking ahead, the convergence of nanotechnology with quantum mechanics, AI, and biotechnology is poised to drive the next wave of scientific and industrial revolutions. Innovations in scalable nanomanufacturing, green nanotechnology, and multifunctional nanomaterials will shape the future, making nanofabrication more efficient, sustainable, and impactful. With continuous advancements, nanofabrication has played a crucial role in shaping the technological landscape of the 21st century,

addressing global challenges, and unlocking new possibilities for scientific discoveries and industrial applications.²²

CONCLUSION

Nanofabrication is an essential pillar of science and engineering in the 21st century, an intermediate between manipulation on the atomic scale and technological breakthroughs of scale. The two-pronged methodological approaches of the discipline, including methods based on the top-down strategies, including photolithography and electron-beam lithography, and methods based on the bottom-up strategies, including molecular self-assembly and atomic-layer deposition, have jointly enabled scholars to achieve exceptional precision and functional diversity of material and device synthesis. The developments have not only increased the pace of semiconductor fabrication as well as microelectronics, but also transformed the activities of biomedical use and include targeted drug delivery systems, biosensors, and tissue-engineering scaffolds. In the same way in the energy and environmental industries, nanofabrication has enabled the creation of high-performance batteries, effective photovoltaic cells and nanostructured catalysts in pollution control.

However, the sector is still facing formidable issues with cost-intensity of the instrumentation, low throughput, compatibility of materials as well as possible environmental risks that might be posed by the generation of nano waste. To overcome these barriers, the next step in the nanofabrication field is also expected to focus on sustainable and scalable manufacturing methods, and put a particular focus on the use of renewable precursors, energy-saving processing, and recycling nanomaterial economies. Moreover, the advent of artificial intelligence, machine learning, and automation promises to bring substantial improvements in the processes optimisation, predictive design, and real-time quality control to improve the reproducibility and efficiency of the operations.

Parallel, cross-disciplinary integration, especially with quantum computing, biotechnology, and soft robotics, is expected to open new possibilities with regard to smart systems,

nanosensors, and adaptive materials. With the ongoing development of nanofabrication, it will become the new way of setting forth the limits of what can be fabricated at the nanoscale to lay the foundation of the next generation technologies which should not only be high-performing but also sustainable and socially responsible. As such, the potential transformational power of nanofabrication will continue to move scientific, industrial and social development forward making it an attractive force in the future of superior materials and devices.

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