

MINI REVIEW



Advanced functional nanomaterials: Design, synthesis, and applications in next-generation devices

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ABSTRACT

Advanced functional nanomaterials have surfaced as a foundation in the development of coming-generation bias, offering unknown openings for enhanced performance across different fields similar as electronics, energy, healthcare, and environmental monitoring. The unique parcels of nanomaterials arising from their reduced dimensionality, high face- to- volume rate, and tunable physical characteristics enable innovative designs and operations. This mini review focuses on the design principles, conflation styles, and advanced operations of nanomaterials in slice- edge bias. Crucial design strategies, including control over morphology, composition, and face variations, are explored in detail. State- of- the- art conflation ways, similar as chemical vapor deposit, sol- gel processing, and green conflation, are stressed for their capability to produce high- quality nanomaterials with scalable and cost-effective approaches. Likewise, recent improvements in operations similar as flexible electronics, high- effectiveness energy storehouse, advanced biosensing, and smart medicine delivery systems are bandied. The review also addresses critical challenges, including scalability, stability, and environmental enterprises, and concludes with perspectives on unborn exploration directions. By furnishing perceptivity into the rearmost developments, this work aims to inspire farther invention in the field of functional nanomaterials for coming- generation technologies.

KEYWORDS

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Introduction

Nanotechnology has revolutionized modern wisdom by enabling the manipulation of paraphernalia at the atomic and molecular scale, leading to the development of nanomaterials with extraordinary parcels. Among them, advanced functional nanomaterials have garnered significant attention due to their enhanced mechanical, optical, electronic, and chemical characteristics, which are unattainable in their bulk counterparts. These unique parcels arise from the quantum size goods, high face area, and tunable face chemistry of nanomaterials, making them ideal contenders for coming-generation bias across various fields.

The rapid-fire- fire advancements in material design and emulsion ways have paved the way for a new generation of bias with bettered performance, effectiveness, and multifunctionality. From high-performance energy storage systems and flexible electronic bias to advanced biosensors and drug delivery systems, functional nanomaterials are at the van of technological invention [1]. Especially, their versatility enables the fabrication of bias with enhanced energy effectiveness, miniaturization, and responsiveness to external stimulants. The rapid-fire advancements in material design and conflation ways have paved the way for a new generation of bias with bettered performance, effectiveness, and multifunctionality.

Design Strategies for Advanced Nanomaterials

The design of advanced functional nanomaterials is vital for

acclimatizing their parcels to meet specific conditions in coming- generation bias. Crucial strategies for optimizing their performance are epitomized below;

Tailoring size and shape

The size and shape of nanomaterials directly impact their parcels. Reducing nanoparticle size to the amount confinement governance enhances optic parcels, as demonstrated by amount blotches in high- resolution displays. Also, nanorods and nanowires promote directional charge transport, making them ideal for transistors and photodetectors [2].

Composition control

Tuning the essential composition of nanomaterials enhances their functionality. Alloyed or doped nanomaterials, similar as doped essence oxides, parade superior catalytic exertion, conductivity, or stability [3]. For illustration, answer silicon nanostructures with boron or phosphorus increases conductivity, perfecting performance in electronic operations.

Surface functionalization

Face functionalization improves the selectivity and biocompatibility of nanomaterials, which is essential for operations in biosensing and medicine delivery. Functionalizing shells with ligands or biomolecules enables targeted relations, similar as gold nanoparticles functionalized with thiol groups for specific biomedical operations.

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Hierarchical and multi-scale structuring

Hierarchical structures combine parcels from different scales, enhancing overall performance. Exemplifications include multilayered graphene for increased mechanical strength and core-shell nanoparticles for controlled medicine release and thermal conductivity [4].

Defect engineering

Defects, such as vacancies and dislocations, can be engineered to enhance parcels like catalytic exertion and charge transport. Disfigurement-rich nanosheets, for case, show superior performance in hydrogen elaboration responses [5].

Synthesis Techniques for Advanced Functional Nanomaterials

The synthesis of advanced nanomaterials is pivotal for controlling their structure, properties, and performance. Synthesis ways are generally classified into top-down and nethermost-up approaches, each with distinct benefits and challenges.

Top-down approaches

Top-down methods involve reducing bulk materials to the nanoscale using physical or chemical means, enabling precise control over nanostructure shape and size [6]. Lithography generally used in semiconductor manufacturing, lithography (e.g., photolithography, electron beam lithography) produces high-resolution nanostructures for transistors and sensors. Etching Wet and dry etching processes widely remove material to produce complex geometries with high aspect ratios.

Bottom-up approaches

Bottom-up methods assemble nanomaterials atom by atom or patch by patch, offering high infinitesimal-position perfection and scalability [7].

Chemical vapour deposition (CVD)

CVD is extensively used to synthesize carbon nanotubes, graphene, and nanowires due to its capability to produce high-purity, invariant nanostructures [8].

Applications in Next-Generation Devices

The rapid development of advanced nanomaterials has opened new frontiers for next-generation devices across fields such as electronics, energy, sensing, and healthcare. These materials exhibit exceptional properties like high conductivity, tunable optics, and mechanical strength, making them ideal for a wide range of applications.

Electronics

Nanomaterials enable smaller, faster, and energy-efficient electronics. Flexible and wearable devices use materials like graphene, carbon nanotubes, and MXenes for high conductivity and flexibility [9]. Two-dimensional (2D) materials, including MoS₂ and black phosphorus, are advancing high-performance transistors, while nanostructured materials are being employed in next-gen memory devices like memristors [10].

Energy storage and conversion

Nanomaterials are revolutionizing sustainable energy

technologies. Advanced electrodes, such as silicon nanowires and transition metal oxides, enhance battery performance. Perovskite nanocrystals and quantum dots improve solar cell efficiency [11].

Sensing technologies

High-sensitivity sensors benefit from nanomaterials in biosensing, gas detection, and photonic applications. Gold nanoparticles, graphene oxide, and metal oxides are used in biosensors and gas sensors. Quantum dots enhance optical sensors for real-time imaging.

Next-generation computing

Neuromorphic devices using memristors and spintronic materials promise breakthroughs in brain-inspired computing and advanced information processing [12].

Current Challenges and Future Perspectives

Despite significant progress in nanomaterials, several challenges limit their large-scale adoption. Scalability remains a key issue, as many synthesis methods like CVD and molecular beam epitaxy (MBE) are expensive and difficult to implement on an industrial scale [13]. Stability is another concern, as nanomaterials often degrade under real-world conditions, affecting performance in applications such as energy storage and biosensing. Ensuring uniformity in nanomaterial properties across large batches also poses a challenge, leading to inconsistent device performance.

Looking ahead, scalable and cost-effective production methods, such as solution-based synthesis, additive manufacturing, and self-assembly techniques, could enable broader use of nanomaterials. Addressing stability issues will require the design of robust hybrid nanomaterials with protective coatings or stable matrices. Future devices may integrate multifunctional nanomaterials for combined sensing, energy harvesting, and data processing, offering new possibilities in fields like smart healthcare and autonomous systems [14,15].

Conclusion

Advanced functional nanomaterials hold immense promise for revolutionizing next-generation devices across a broad spectrum of applications, from flexible electronics to sustainable energy and precision medicine. Despite significant progress in their design and synthesis, several challenges remain. The scalability of synthesis techniques is a critical bottleneck, as many high-performance nanomaterials are currently produced using methods that are costly, time-consuming, or environmentally hazardous. Ensuring reproducibility and uniformity at an industrial scale is another major hurdle, particularly for devices requiring precise control over nanoscale features. Moreover, the long-term stability of nanomaterials under operational conditions, including mechanical stress, temperature variations, and exposure to environmental agents, needs to be improved for their widespread adoption in real-world devices. Additionally, environmental and health concerns related to nanomaterial synthesis and disposal must be addressed by developing greener, more sustainable production processes.

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

1. Kong F, Zhang H, Qu X, Zhang X, Chen D, Ding R, et al. Gold Nanorods, DNA Origami, and Porous Silicon Nanoparticle-functionalized Biocompatible Double Emulsion for Versatile Targeted Therapeutics and Antibody Combination Therapy. *Adv Mater* (Deerfield Beach, Fla.). 2016;28(46):10195-10203. <https://doi.org/10.1002/adma.201602763>
2. Sharma R, Sharma PK, Malviya R. Modulation of shape and size-dependent characteristics of nanoparticles. *Curr Nanomed*. 2019; 9(3):210-215. <https://doi.org/10.2174/2468187309666190301153651>
3. Liu J, Zhang T, Waterhouse GI. Complex alloy nanostructures as advanced catalysts for oxygen electrocatalysis: from materials design to applications. *J Mater Chem A*. 2020;8(44):23142-23161. <https://doi.org/10.1039/d0ta09092a>
4. Yin PT, Shah S, Chhowalla M, Lee KB. Design, synthesis, and characterization of graphene-nanoparticle hybrid materials for bioapplications. *Chem Rev*. 2015;115(7):2483-2531. <https://doi.org/10.1021/cr500537t>
5. Zhang Y, Kuwahara Y, Mori K, Yamashita H. Defect engineering of MoS₂ and its impacts on electrocatalytic and photocatalytic behavior in hydrogen evolution reactions. *Chem Asian J*. 2019;14(2):278-285. <https://doi.org/10.1002/asia.201801594>
6. Harish V, Ansari MM, Tewari D, Gaur M, Yadav AB, García-Betancourt ML, et al. Nanoparticle and nanostructure synthesis and controlled growth methods. *Nanomater*. 2022;12(18):3226. <https://doi.org/10.3390/nano12183226>
7. Begley MR, Gianola DS, Ray TR. Bridging functional nanocomposites to robust macroscale devices. *Sci*. 2019;364(6447): eaav4299. <https://doi.org/10.1126/science.aav4299>
8. Manawi YM, Ihsanullah, Samara A, Al-Ansari T, Atieh MA. A review of carbon nanomaterials' synthesis via the chemical vapor deposition (CVD) method. *Mater*. 2018;11(5):822. <https://doi.org/10.3390/ma11050822>
9. Ma C, Ma MG, Si C, Ji XX, Wan P. Flexible MXene-based composites for wearable devices. *Adv Funct Mater*. 2021;31(22):2009524. <https://doi.org/10.1002/adfm.202009524>
10. Wang M, Zhu J, Zi Y, Wu ZG, Hu H, Xie Z, et al. Functional two-dimensional black phosphorus nanostructures towards next-generation devices. *J Mater Chem A*. 2021;9(21):12433-12473. <https://doi.org/10.1039/D1TA02027G>
11. Aftab S, Li X, Hussain S, Aslam M, Rajpar AH, Al-Sehemi AG. Nanoscale enhancements in perovskite-based photovoltaics. *Chem Eng J*. 2024;480:148143. <https://doi.org/10.1016/j.cej.2023.148143>
12. Zhou J, Chen J. Prospect of spintronics in neuromorphic computing. *Adv Electron Mater*. 2021;7(9):2100465. <https://doi.org/10.1002/aelm.202100465>
13. Deng B, Liu Z, Peng H. Toward mass production of CVD graphene films. *Adv Mater*. 2019;31(9):1800996. <https://doi.org/10.1002/adma.201800996>
14. Albertini PP, Newton MA, Wang M, Segura Lecina O, Green PB, Stoian DC, et al. Hybrid oxide coatings generate stable Cu catalysts for CO₂ electroreduction. *Nat Mater*. 2024;23(5):680-687. <https://doi.org/10.1038/s41563-024-01819-x>
15. Jeong HH, Alarcón-Correa M, Mark AG, Son K, Lee TC, Fischer P. Corrosion-Protected Hybrid Nanoparticles. *Adv Sci*. 2017;4(12): 1700234. <https://doi.org/10.1002/advs.201700234>