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Introduction to the editor's choice collection on Nanoarchitectonics: fine structure construction in nanoscale

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Nanoscale Horizons Board member, Professor Katsuhiko Ariga (National Institute for Materials Science & The University of Tokyo), introduces this Editor's Choice collection in *Nanoscale Horizons*, *Nanoscale* and *Nanoscale Advances*, on Nanoarchitectonics: fine structure construction in nanoscale.

Humanity's progress is heavily reliant on the variety of available materials. Throughout the 20th century, different academic disciplines developed, allowing for the creation of materials in a more structured manner. Scientists observed a recurring theme as these fields evolved. The material's physical properties are primarily influenced by its structure and internal arrangement as well as its composition itself. Controlling the structure and developing the function at atomic, molecular, and nanoscale levels is crucial. The trend was fuelled by the development and creation of nanotechnology. Advanced nanotechnology enables the direct observation of atomic and molecular structures through multiple scientific methods. The investigation of physical properties at an extremely small scale has now started. Introducing a concept is thought to significantly accelerate this development trend. Nanoarchitectonics as a post-nanotechnology concept is set to take on that role.[1]

The method of nanoarchitectonics creates functional material systems by using atoms, molecules, and nanomaterials as individual building blocks. This methodology is versatile and can be applied to a broad spectrum of applications. It is applied in core areas such as material synthesis, structural assembly, physical properties, and biochemistry, plus applications involving catalysts, sensors, equipment, and energy, the environment, and biology. Since all materials are composed of atoms and molecules, this approach can be applied universally to all materials. Therefore, the concept of nanoarchitectonics might be regarded as a universal approach in materials science, a method for everything.[2] Nanoarchitectonics has been applied in a range of applications and fields, from regulating atom-level structures[3] to complex organizations with biomolecules.[4] Research in the field of nanoarchitectonics is experiencing a surge in activity.[5–9] Nanoarchitectonics can be viewed in terms of methods for building fine structures at the nanoscale, even if they are not publicly disclosed. In this editor's choice collection, we demonstrate the scope of its capabilities through recent examples from *Nanoscale Horizons*, *Nanoscale* and *Nanoscale Advances* scientific publications.

Distinct outputs of the nanoarchitectonics approach would be the preparation of novel materials structures with nanostructure precision for interesting properties. Ramulu *et al.* (**https://doi.org/10.1039/D3NR02103C**) prepared hetero-nanoarchitectures incorporating two or more transition metal selenides, iron-nickel selenide spring-lawn-like architectures on nickel foam. The reported nanoarchitectonics approach may initiate a strategy of advanced metal selenide-based materials for multifunctional

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applications. Sugi *et al.* (**https://doi.org/10.1039/D3NR02561F**) presented a secondary ligand-induced orthogonal self-assembly of atomically precise silver nanoclusters into complex superstructures, specifically using Ag_{14} nanoclusters protected with naphthalene thiol and 1,6-bis(diphenylphosphino)hexane ligands. This nanoarchitectonics demonstrates that by tuning supramolecular interactions, hierarchical nanostructures with desired properties similar to biomolecules can be obtained from atomically precise building blocks. Martínez *et al.* (**https://doi.org/10.1039/D4NR02484B**) revealed that three-photon upconversion processes predominantly occur at hot-spots in nanowire junctions, contributing to heightened luminescence intensity on Ag nanowire networks. Plasmonic nanoarchitectures have proven potential for amplifying upconversion luminescence signals, prompting investigations into localized enhancement effects within noble metal nanostructures. Ruiz-Hitzky and Ruiz-Garcia (**https://doi.org/10.1039/D3NR03037G**) discussed the nature of MXenes in comparison with clay phyllosilicates, taking into account their structural analogies, outstanding surface properties and advanced applications in their review. These current in-depth understandings of clay minerals may represent a basis for the future development of MXene-derived nanoarchitectures. Wang *et al.* (**https://doi.org/10.1039/D3NR03578F**) designed a composite hydrogel with high mechanical strength, rapid self-recovery and efficient self-healing ability based on multiple synergistic effects. In this nanoarchitectonics approach, multifunctional composite hydrogels exhibit excellent anti-freezing, moisturising, self-healing, transparency and shape memory properties. Li *et al.* (**https://doi.org/10.1039/D5NR00148J**) fabricated a long-range ordered organic quantum corral (QC) array *via* the self-assembly of 1,3,5-benzenetribenzoic acid molecules onto the herringbone reconstructed Au(111) surface. This nanoarchitectonics approach shows that combined molecular and non-organic patterning can serve as a promising tool to macroscopically tune the electronic properties of metal surfaces in a controllable manner.

Structure regulations by nanoarchitectonics approaches are highly useful for designs and fabrications of devise-related functions. Arora *et al.* (**https://doi.org/10.1039/D4NR04138K**) reported a nanoarchitectonics approach to synthesize Bi_2S_3 nanorods and decorate them with FeS to form an FeS-Bi_2S_3 heterostructure *via* a one-step, template-free hydrothermal method. The presented results provide insights into tailoring the heterostructure of different transition metals with Bi_2S_3 and studying their field emission behaviours. Noh *et al.* (**https://doi.org/10.1039/D2NH00375A**) provided a nanoarchitectonics method for the realization of a 2D patterned array of individually addressable Vanadyl Phthalocyanine spin qubits. The obtained results pave a viable route towards the future integration of molecular spin qubits into solid-state devices. Candia *et al.* (**https://doi.org/10.1039/D5NR01235J**) prepared three canonical cross-conjugated quasi one-dimensional chains with controlled nitrogen intrinsic doping, which is selectively introduced into their poly-phenylene backbones. Nanoarchitectonics of quasi-one-dimensional polymer structures with extended pi-electron systems would be useful for light-emitting diodes and devices. Bogachuk *et al.* (**https://doi.org/10.1039/D2NR05856A**) utilized a sacrificial film of polystyrene nanoparticles to introduce nano-cavities into mesoporous metal oxide layers, enabling the growth of larger perovskite crystals inside the oxide scaffold with significantly suppressed non-radiative recombination and improved device performance. Their work exemplifies potential applications of such nanoarchitectonic approaches in perovskite opto-electronic devices.

Applications towards energy demands are hot topics in current science and technology. Use of the nanoarchitectonics approach in energy-directed applications and related catalytic performances is an area of active research. Bo *et al.* (**https://doi.org/10.1039/D4NR04763J**) reported the preparation of mixed-valence lead oxide materials with a unique hierarchical nanoarchitecture for outstanding electrochemical reactivity and mechanical robustness in lithium storage and various potential applications. Kim *et al.* (**https://doi.org/10.1039/D5NR00556F**) synthesized Zn-based zeolitic imidazolate framework (ZIF-8) nanocrystals with controlled sizes and a narrow size distribution, resulting in nanoporous polyhedral carbon nanoarchitectures for the performance evaluations of supercapacitors This nanoarchitectonics approach offers valuable insights into the utilization of nanoporous carbons across diverse electrochemical applications. Akir *et al.* (**https://doi.org/10.1039/D3NR01144E**) demonstrated experimental studies of V_2C MXene-based materials containing two different bismuth compounds to confirm the possibility of using V_2C as a potential electrocatalyst for the hydrogen evolution reaction and nitrogen reduction reaction. These nanoarchitectonics achievements present a high performance in terms of the highest generated NH_3 compared to recent investigations of MXenes-based electrocatalysts. Xu *et al.* (**https://doi.org/10.1039/D4NR01537A**) synthesized petal-like PdAg nanosheets with an ultrathin 2D structure and jagged edges *via* a facile wet-chemical approach, combining doping engineering and morphology tuning. The nanosheets promote efficient electrocatalytic oxidation of ethanol and methanol. Li *et al.* (**https://doi.org/10.1039/D3NA00182B**) established an m-$BiVO_4$/carbon nitride (C_3N_4) Z-scheme heterostructure based on the m-$BiVO_4$/reduced graphene oxide (rGO) Mott–Schottky heterostructure, constructing the face-contact C_3N_4/m-$BiVO_4$/rGO ternary composite to remove excessive surface recombination during water oxidation. This nanoarchitectonics approach shows a novel perspective for rationally integrating Z-scheme and Mott–Schottky heterostructures in the water oxidation reaction. Kumar *et al.* (**https://doi.org/10.1039/D3NA00094J**) provided a comprehensive evaluation of the potential of carbon-based materials in enhancing the electrochemical performance of supercapacitors together with their combination of these materials with other cutting-edge materials, such as transition metal dichalcogenides, MXenes, layered double hydroxides, graphitic carbon nitride, metal–organic frameworks, black phosphorus, and perovskite nanoarchitectures. This review article aims to highlight these challenges and provide insights into the potential of carbon-based materials in supercapacitor applications.

From basic chemistry to practical biomedical applications, nanoarchitectonics approaches can be actively used in bio-related fields. Fornerod *et al.* (**https://doi.org/10.1039/D4NH00466C**) introduced a bottom-up fabrication process based on the self-assembly of high molecular weight block copolymers with sol–gel precursors to create an inorganic nanoporous thin film directly on electrode surfaces. The nanoarchitecture efforts would be a significant step towards a portable, rapid, and accurate DNA detection system. Yum *et al.* (**https://doi.org/10.1039/D3NR01625K**) reported on the construction of Cu-histidine (His)-DNA hybrids as laccase-mimetic DNAzymes. Cu-His-DNAzymes showed remarkable activity in a colorimetric oxidation reaction between 2,4-dichlorophenol and 4-aminoantipyrine. The obtained results provide new insights for the systematic construction of tailor-made active sites for biomimetics. Song *et al.* (**https://doi.org/10.1039/D4NR00609G**) reviewed construction strategies and functions of bio-gel nanoarchitectonics in medical applications and tissue engineering. Specifically, it discussed (i) hydrogel bio-inks for 3D bioprinting, (ii) dynamic hydrogels as an artificial extracellular matrix (ECM), and (iii) topographical hydrogels for tissue organization. Dotor *et al.* (**https://doi.org/10.1039/D2NR06631A**) took advantage of the nanoarchitectonic capabilities of the Langmuir technique for the construction of model cell membranes and determination of thermodynamic properties in mixed films. The obtained results may serve to provide some light on the miscibility of curcumin with the components in the cell membrane and to determine the optimal conditions for the fabrication of membrane systems incorporating curcumin. Pagendarm *et al.* (**https://doi.org/10.1039/D3NR02874G**) implemented a flash nanoprecipitation approach to produce nanocarriers of diverse vesicular morphologies by using various molecular weight polymers. This nanoarchitectonics approach enables access to a diverse variety of nanoarchitectures including micelles, unilamellar vesicles (polymersomes), and multicompartment vesicles, which are useful in the delivery of distinct biomolecular cargos for other therapeutic applications, indicating the therapeutic potential of this platform in an array of disease applications.

I hope that this editor's choice collection will demonstrate the diverse possibilities of the new concept of nanoarchitectonics. Nanoarchitectonics is a developing concept, and thus I hope that many researchers will participate. Finally, I would like to express my sincere gratitude to the dedicated authors, reviewers, and editorial staff for their valuable contributions to this thematic collection of papers.

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