Advanced nanomaterials for energy conversion and storage: current status and future opportunities

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Fabricating nanostructured materials with tailored properties is at the forefront of technological exploration. At present, novel strategies such as size/facet control, structural engineering, vacancy engineering, atomic regulation, and construction of nanocomposites alter the physicochemical properties (e.g. electronic, optical, band and textual) of the active sites. Hence, this gives rise to a momentous improvement in the performance of nanomaterials toward energy conversion and storage. Research in this energy realm necessitates an interdisciplinary approach with synergistic collaboration from all disciplines such as chemistry, engineering, nanotechnology, computation, as well as industrial thinking to accomplish high-performance energy systems.

The themed collection of Nanoscale entitled “advanced nanomaterials for energy conversion and storage” aims to showcase the state-of-the-art knowledge on the development of nanomaterials with tunable properties for diverse energy applications. This themed collection consists of 23 Full Papers, 4 Communications and 5 Reviews, focusing on designing advanced materials and building a structure–activity–stability relationship in electrocatalysis, photocatalysis, photoelectrocatalysis, batteries, fuel cells and so forth.

Xiong et al. (DOI: 10.1039/D0NR02596H) highlight the development of engineering active sites on surfaces and in open frameworks with respect to surface vacancies, doped heteroatoms, loaded metal nanoparticles, crystal facets and metal nodes/organic linkers in metal–organic frameworks for application in photocatalytic CO₂ reduction. In addition to the advances in CO₂ photoreduction, Zhang et al. [DOI: 10.1039/D0NR03178J] have reviewed the use of carbon-based nanomaterials and their hybrids for photo- and electrocatalytic hydrogen peroxide (H₂O₂) production via both reductive and oxidative reaction pathways. Apart from photochemistry, inspired by the merits of 2D nanostructures, Tsang’s group [DOI: 10.1039/D0NR0295E] present a minireview on the recent discoveries in hetero-single atom-doped MoS₂ nanosheets for electrochemical hydrogen evolution reaction (HER) from water by reviewing the nature of the dopants, doping positions and the polytypes of MoS₂. In view of the importance of morphological engineering in energy applications, Wang et al. [DOI: 10.1039/D0NR03425H] focus on the primary issues facing one-dimensional (1D) electrospun carbon nanofibers in supercapacitors with the aim of ameliorating the conductivity, modulating pore configuration, doping with heteroatoms and increasing mechanical strength. Sun et al. [DOI: 10.1039/D0NR05475E] summarize the most recent updates on the structure–activity relationship of random alloy and intermetallic (ordered structure) nanocrystals for electrochemical fuel cells with robust activity and superb stability.

By mimicking natural photosynthesis, artificial photosynthesis using nanocatalysts is described by several research groups. For enhancing the light absorp-
and inhibiting the electron–hole recombination, morphological modification and surface engineering are facile techniques to boost photocatalysis.\(^5\)\(^,\)\(^7\) Tang et al. (DOI: 10.1039/D0NR00226G) have prepared graphitic carbon embedded inside hollow graphitic carbon nitride \((g\text{-}C_3N_4)\). Yu’s group (DOI: 10.1039/C9NR04511H) successfully developed hierarchical Ni-NiS/C/ZnO photocatalysts via in situ photodeposition of Ni-NiS nanosheets onto C/ZnO electrospun nanofibers for \(\text{CO}_2\) reduction to CO and \(\text{CH}_4\). Attributed to the advantages of 2D/2D heterojunction systems, Jing et al. (DOI: 10.1039/D0NR05511H) fabricated dimension-matched ultrathin NiMOF/g-C\(_3\)N\(_4\) heterojunctions with the aid of ultrasound by growing NiMOF nanosheets on hydroxylated and 1,4-aminobenzoic acid functionalized g-C\(_3\)N\(_4\) nanosheets for improved \(\text{CO}_2\) reduction. To aim for energy sustainability as opposed to the energy-intensive industrial Haber–Bosch process, Tang et al. (DOI: 10.1039/D0NR02527E) designed a ternary heterostructure consisting of ruthenium species on g-C\(_3\)N\(_4\) \((\text{Ru/RuO}_2/g\text{-}C_3\text{N}_4)\) for ammonia photosynthesis, in which Ru and RuO\(_2\) functioned as electron and hole storage sites, respectively. Furthermore, Zhang et al. (DOI: 10.1039/D0NR03393F) report W-doped TiO\(_2\) for boosted photothermal catalytic \(\text{CO}_2\) reduction to CO due to the presence of more active sites with increased W doping. By applying an external bias, Jorge et al. (DOI: 10.1039/D0NR06139E) introduce a carbon underlayer derived from carbon dots via a hydrothermal process between the fluorine-doped tin oxide substrate and the hematite photoanodes, which has remarkably enhanced the photocurrent density and charge transfer efficiency of up to ca. 80% at 1.25 V vs. RHE. Besides energy conversion, An’s group (DOI: 10.1039/D0NR01027H) has synthesized well-aligned 2D Ni-MOF nanosheet arrays vertically grown on porous nickel foam \((\text{Ni-MOF/NF})\) without lateral stacking via solvothermal processes for the removal of ethyl acetate. Falaras’s group (DOI: 10.1039/D0NR02562C) designed an innovative interface engineering approach to utilize an organic chromophore as an

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Nanfeng Zheng received his B.S. from Xiamen University in 1998. In 2003, he obtained his Ph.D. degree from University of California – Riverside. During 2005–2007, he worked as a research associate at University of California – Santa Barbara. He moved to Xiamen University as a Full Professor in 2007 and became a Changjiang Chair Professor in 2010. He is currently the executive deputy director of Innovation Laboratory for Sciences and Technologies of Energy Materials of Fujian Province (IKKEM). His research is committed to understanding the surface and interface chemistry behind the factors regulating the properties of functional materials at the molecular level and thus promoting their applications in the fields of energy, catalysis, and environmental protection.

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Markus Antonietti is the Materials Chemistry Director of the Max Planck Institute of Colloids and Interfaces in Potsdam-Golm, Germany. He is an expert in polymers and covalent materials and has focused his attention in the last years to the fields of green chemistry and sustainable materials, but also to the new global cycles of energy, food, water, and \(\text{CO}_2\) constituting the Anthropocene. In his free time, he enjoys cooking and performing in a rock band.
interlayer between a perovskite absorber and hole transporter, which preserved 83% of the original efficiency despite storing the device for 37 days in the dark and under open-circuit conditions.

In addition to light-driven reactions, research in the field of electrocatalysis for water splitting and CO₂ reduction is a prime focus of sustainable energy research.⁶⁻¹¹ As a low-cost alternative to Pt, Yamashita’s group (DOI: 10.1039/D0NR02525A) employed the noble-metal-free hybrid phase 1T/2H-MoS₂ with tunable 1T concentration for electrochemical hydrogen evolution. Oh et al. (DOI: 10.1039/D0NR02951C) studied the pH influence on the electro-activation of IrNi alloy nanoparticles supported on carbon (IrNi/C) toward water oxidation, where different pH conditions led to extraordinary electronic structure by modifying the alloy catalysts. Liu et al. (DOI: 10.1039/D0NR03378B) developed trifunctional electrocatalysts for hydrogen evolution (HER), oxygen evolution (OER) and oxygen reduction reactions (ORR), which are composed of a hierarchically-structured Pt/NiO/Ni/CNT with around 2 nm of Pt nanoparticles via substrate-enhanced electroless deposition. Beyond water splitting for hydrogen and oxygen evolution reactions, Luo et al. (DOI: 10.1039/D0NR02591G) synthesized nanostructured Cu@Cu₂(OH)₂NO₃ electrodes via a molten salt decomposition method (MSDM) for CO₂ electroreduction to C₂H₄ in KHC₃O₃ solution with a high faradaic efficiency of 31.8% and robust stability of over 20 h. In another investigation, Chen’s group (DOI: 10.1039/D0NR03475D) unravelled the effect of the dynamic chemical state on the selective CO₂ reduction to CO and formate using Zn electrocatalysts via in situ Raman spectroscopy, X-ray absorption spectroscopy (XAS) and X-ray diffraction, in which Znₙ⁺ and Zn₀ species played a dominant role in CO and formate production, respectively. Li et al. (DOI: 10.1039/C9NR10304J) employed a series of an electrochemical method and in situ SERS to elucidate the size effects of Pt on the activity of Pt-on-Au nanocatalysts with a Au-core Pt-satellite superstructure toward CO and methanol electrooxidation. Other than that, by taking the merits of the appealing optoelectronic and electrochemical attributes of MXene, Gogotsi et al. (DOI: 10.1039/D0NR02673E) fabricated solution processable transparent conducting electrodes for three-electrode electrochemical cells by employing titanium carbide MXenes. Along another energy conversion route, Hong et al. (DOI: 10.1039/D0NR03303K) examined thermoelectricity in molecular junctions developed from oligophenylene-ethynylene derivatives.

Advances in energy storage devices using nanotechnology is another global trend of energy research.³⁻¹³ Xu et al. (DOI: 10.1039/D0NR02016H) prepared multilayered nickel–cobalt organic framework (NiCo-MOF) nanosheets as robust electrode materials for excellent electrochemical energy storage over 3000 cycles at 5 A g⁻¹. Kowalenko et al. (DOI: 10.1039/D0NR02930K) present the synthesis of homogeneously embedded Sb nanoparticles in a silicon oxycarbide (SiOC) matrix, which was able to provide a reasonably high Li-ion storage capacity. Hwang et al. (DOI: 10.1039/D0NR02569K) designed the intercalative hybridization of MoS₂ with chromium hydroxide nanoclusters, which increase the basal spacing, accelerate charge kinetics and stabilize the open porous stacking structure for boosted charge storage capacity and rate performance for Li-ion batteries.⁴ In Li–S batteries, sluggish dynamics of lithium polysulfides (LiPS) conversion results in fast capacity decay and ineffective utilization of active sulfur. Wu et al. (DOI: 10.1039/D0NR03528A) designed a hierarchical MXene@TiO₂ nanoarray via in situ solvo-thermal strategies, which is able to retain a stable discharge capacity of 612.7 mAh g⁻¹ after 500 cycles at a rate of 2C in a Li-S battery. In another related work, a ZnS quantum dot@graphene nanosheet (ZnS QD@rGO) catalyst was fabricated by Wei and coworkers (DOI: 10.1039/D0NR02429E) to ameliorate polysulfide conversion for high energy density Li-S batteries. By blocking the LiPS shuttling, the construction of an interlayer with low Li ion diffusion resistance renders a magnificent approach. Lv et al. (DOI: 10.1039/D0NR02607G) constructed a thin porous carbon nanosheet with embedded TiO₂ nanoparticles as an interlayer on the separator, which allows rapid Li ion diffusion and simultaneously blocks the polysulfide diffusion. In another work, Lee et al. (DOI: 10.1039/D0NR02258F) engineered a Li metal anode by employing microporous and mesoporous carbon as host materials to avoid degradation during cycling of Li–S batteries.

Other than Li batteries, Dong and Wang et al. (DOI: 10.1039/D0NR02604B) reported the design of a walnut-like MoS₂@SnS core-shell heterostructure as an anode for sodium-ion batteries, which exemplified superior electrochemical performances ascribed to improved ion diffusion at the heterointerface driven by an internal electric field. To circumvent shortcomings present in organic potassium batteries (PIB), Zhang et al. (DOI: 10.1039/D0NR00964D) designed a non-redox-metal potassium metal–organic framework (K-MOF) as an auspicious organic anode for high electrochemical performance and cycling for more than 300 cycles with capacity retention of 92% stemming from the N–K/O–K coordination bonds. Apart from the organic anode, Mai’s group (DOI: 10.1039/D0NR01274B) constructed self-adaptive NiSₓ nanoparticles embedded in three-dimensional (3D) graphene oxide as a robust anode with outstanding rate behaviour and high reversible capacity in PIB with reversible transformation from NiSₓ to KₓNiSₓ followed by generating Ni and KₓSₓ products. Bifunctional OER/ORR electrocatalysts composed of N-doped carbon nanotubes containing NiFe alloy nanoparticles were fabricated by Zhang et al. (DOI: 10.1039/D0NR02486D), in which an excellent performance for rechargeable zinc-air batteries was ascribed to the high porosity and boosted conductivity, hence benefiting mass and electron transfer processes.

We are certain that this themed collection will inspire the readers to further advance fundamental understanding of the state-of-the-art energy applications to potentially meet the industrial requirements for commercialization and globalization. As Guest Editors, we would like to thank all invited authors for their...
excellent contributions as well as all Nanoscale’s editors and reviewers for their selfless professional services. On a final note, in conjunction with the Xiamen University’s anniversary in 2021, we would like to commemorate and congratulate on the 100th anniversary of Xiamen University, China and the 5th anniversary of Xiamen University Malaysia campus. In view of the university’s anniversary, we would like to celebrate the successful launch of the Center of Excellence for NaNo Energy & Catalysis Technology (CONNECT) at Xiamen University Malaysia in 2021.

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