

3D printed electrodes for bubble management in high-rate water electrolysis

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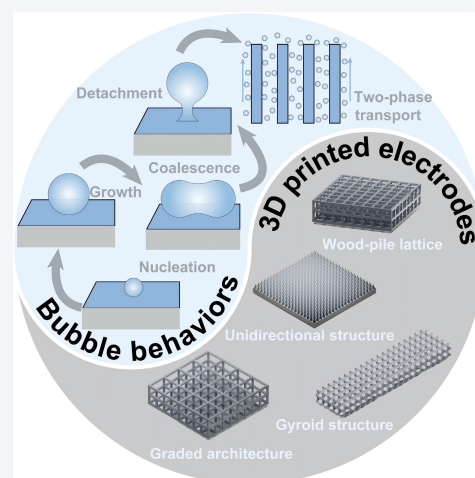
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 Cite this article: Nano Research, 2026, 19, 94908521. <https://doi.org/10.26599/NR.2026.94908521>

ABSTRACT: High-rate water electrolysis ($> 400 \text{ mA} \cdot \text{cm}^{-2}$) is pivotal for scalable green hydrogen production, yet the intense gas evolution within three-dimensional (3D) electrodes limits both electrolysis efficiency and long-term stability. This review examines how 3D printing revolutionizes electrode design to optimize bubble management. The techniques, such as direct ink writing (DIW), vat photopolymerization (VP), and selective laser melting (SLM), enable the fabrication of complicated electrode architectures which surpass conventional 3D electrodes with stochastic pores. We classify the designs into two families, including periodic ordered structures and functionally graded and directional architectures. By integrating *operando* high-speed imaging with multiphysics simulation, recent studies reveal how macroscopic topology, pore geometry, and nanoscale morphological engineering synergistically reduce the three-phase contact length, accelerate bubble detachment, and lower the mass transport resistance while balancing electrochemical surface area. Despite being an emerging area, architected 3D printed electrodes offer a promising approach to breakthrough in high-rate water electrolysis. In light of recent reports, we also identify the key challenges and present an outlook on interdisciplinary research of 3D printing and bubble management at the end of this review, with the aim that this review serves as a helpful reference for the continued development of the field.

KEYWORDS: three-dimensional (3D) printing, electrode, architecture, water electrolysis, bubble management



1 Introduction

Water electrolysis has been extensively studied as one key technology realizing sustainable and decarbonized energy systems [1, 2], converting renewable electrical energy into the chemical energy stored in molecular hydrogen. For electrolyzers to be competitive at industrial scale, they must be able to run at high-rate conditions ($> 400 \text{ mA} \cdot \text{cm}^{-2}$) with low cell voltage and long-term stability. Meeting those metrics requires not only active and durable catalysts

but also careful management of bubble departure and two-phase transport at the electrode/electrolyte interfaces [3–5].

The bubble dynamics during water electrolysis influence efficiency, and are primary determinants of electrode performance under high-rate conditions because gas production rates increase significantly with electrical current. The adherent or slowly released bubbles reduce the electrochemical surface area (ECSA) by physically masking the active sites (Fig. 1) [6]. These persistent bubbles residing on the electrode surface also increase the ionic resistance and generate “dead volume”, raising the mass transport overpotentials, which decreases the voltage efficiency of the electrolyzers [7, 8]. Moreover, the bubble adhesion and departure at large size impose significant mechanical stress on the coating of the catalysts that can cause stripping or delamination of active species over time [6], compromising the structural integrity and long-term stability of the electrodes (Fig. 1).

Received: January 4, 2026; Revised: January 30, 2026

Accepted: February 1, 2026

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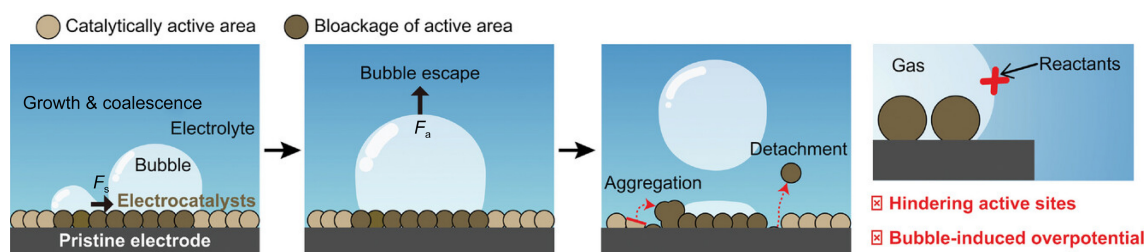


Figure 1 The schematics illustrating negative impacts of bubbles on the electrochemical properties of electrodes. Reproduced with permission from Ref. [9], © Wiley-VCH GmbH 2023.

To mitigate these detrimental effects, rational electrode architecture design represents an effective strategy to regulate bubble dynamics during high-rate electrolysis. Three-dimensional (3D) porous electrodes are widely employed due to their high surface area for supporting active species and the ease in engineering the surface wettability. However, conventional porous 3D electrodes commonly use metal foams (e.g., nickel foam (NF)). Their irregular and stochastic pore architectures tend to trap bubbles on the foam skeletons, further exacerbating the issues by extending the bubble residence time, promoting coalescence into larger bubbles, and degrading high-rate performances [10].

3D printing offers uniquely powerful technique to address these aforementioned issues because it enables controlled fabrication of electrode architectures that are difficult or impossible to realize by conventional chemical methods [11]. By leveraging the computer-designed topologies and tailored porosity, 3D printing allows the creation of electrodes that incorporate flow channels to guide bubble transport and features controlled spatial porosity to balance ECSA and mass transfer. These advanced capabilities directly mitigate the core mechanistic bottlenecks in high-rate water electrolysis, including prolonged bubble residence time, excessive coalescence, impeded mass transfer, and reduced active sites exposure.

Although the literature on 3D printed electrodes for bubble control is still limited, notable advances in recent years have demonstrably improved bubble dynamics in high-rate water electrolysis [10, 12–15]. Whereas prior reviews [16–22] have emphasized printing technique or materials development, this review primarily focuses on 3D printed electrode architectures optimized to control bubble behavior, which is an under-explored but essential direction for industrial-scale electrolysis. We organize the recent designs into two primary classes, including periodic ordered structures and functionally graded and directional architectures for bubble management. The modulation of bubble dynamics by structural design is introduced and discussed in detail in this review, and we close with perspective intended to serve as a timely reference for researchers developing 3D printed electrodes for high-rate electrolysis.

2 Bubble dynamics and 3D printing technologies

2.1 Bubble dynamics

The gas evolving typically includes bubble nucleation, growth, coalescence, and detachment [23]. Bubble nucleation is the first step in bubble dynamics during water electrolysis. When the electrolyte becomes supersaturated, dissolved gas nucleates at the electrode surface. In the early stage, bubble nucleation is hindered by interfacial tension. The classical nucleation theory defines a critical

radius (r_{crit}) for a gas nucleus in a supersaturated electrolyte [24]. The r_{crit} marks the threshold for transition from an unstable to a stable nucleus. Bubbles grow only when their radii are larger than r_{crit} . Otherwise, these bubbles will redissolve under interfacial tension penalties. The equation for the critical radius is shown in Eq. (1) [25]

$$r_{\text{crit}} = \frac{2\gamma}{\Delta P} \quad (1)$$

where γ is the gas–liquid interfacial tension, and ΔP is the pressure difference between the bubble interior and the surrounding liquid. Once nucleated, bubbles enter the growth stage, and they grow at the electrode surface through a “direct injection” mode in which the dissolved gas species diffuse into the gas bubbles, resulting in their volume increase [25, 26]. As bubbles grow, the neighboring bubbles contact one another and begin to coalesce [23]. This is a surface-tension-driven process, and the phenomenon is more likely when nucleation density and gas production rate are high. Part of the surface energy can be released by bubble coalescence and is used to overcome viscous dissipation caused by bubble deformation and the adhesion energy, while the rest of the surface energy is converted into kinetic energy, facilitating detachment of the bubbles from the electrode [27]. The resulting larger bubbles with lower specific surface energy tend to form stable ensembles on the surface, but the increased buoyance facilitates their departure from the electrode surface, re-exposing the surface sites for the renewed cycles of bubble evolving. The bubble size at detachment (R_d) is described by Eq. (2) [28]

$$R_d = \left(\frac{3\gamma R_c}{2\rho g} \right)^{1/3} \quad (2)$$

where R_c represents the radius of bubble/electrode interfacial contact area, and ρ and g are the electrolyte density and gravitational constant, respectively. Creating roughened electrode surface by introducing nanostructured morphology increases wettability, which favors minimizing the pinning area and the R_c [29, 30]. This strategy eventually decreases the bubble size at detachment, ensuring the integrity of the active sites for re-exposure to reactants. However, the nanoscale morphological engineering has limited influence on bubble transport once bubbles detach from the catalyst surface. The gas bubbles detached must still evacuate from the 3D electrode interior, necessitating advanced fabrication methods to create optimized architectures for efficient two-phase flow. Such capabilities are enabled by 3D printing technologies, which offer facile control over electrode structures, as detailed in the next subsection.

2.2 3D printing technologies

3D printing can be classified into different categories based on the

principles (Fig. 2). For example, powder bed fusion like selective laser melting (SLM) directly fuses metal powders and produces scaffolds with inherent surface roughness, often yielding electrically conductive metallic substrate [31, 32]. The vat photopolymerization (VP) and its variants, such as stereolithography (SLA), digital light processing (DLP), and projection micro-stereolithography (PμSL), cure photosensitive resins layer-by-layer with patterned light and attain high resolution, making it attractive for high-precision lattices and arrays [33–35]. SLA uses ultraviolet (UV) laser to trace and cure successive resin layers, producing high-fidelity parts with typical minimum features in the tens of microns [36]. DLP replaces the scanning laser with a digital-micromirror projector that exposes entire layers at once, and offers substantially higher resolution [37]. PμSL differs from conventional SLA or DLP by using high-resolution projection optics to expose each resin layer, enabling precision fabrication at micron scale [38]. Direct ink writing (DIW) extrudes viscoelastic inks (including metal pastes and composite inks) and excels at multi-material printing, graded porosity, and embedding active phases within printed scaffolds [39, 40]. Both the VP and DIW printing require post-printing treatment to either enhance electrical conductivity by plating metal, remove polymer binder or improve the structural robustness through thermal annealing. These 3D printing technologies provide the precision and flexibility needed to prepare complex electrode architectures that address bubble-related challenges in water electrolysis, as

explored in the following section on the specific designs for bubble management.

3 3D printed electrode architectures

3.1 Periodic ordered structures

The central design logic of periodic ordered structures is to replace the stochastic pore networks that dominate conventional metal foams (such as NF), with aligned and predictable through-plane channels that guide bubble transport, reduce bubble residence time, and suppress bubble coalescence. For example, in our previous work [10], we fabricated a DIW 3D printed Ni (3DPNi) lattice with periodic pores based on the hypothesis that aligned pores would promote the buoyancy-driven upward transport of gas bubbles. Carbon-doped NiO ($C-Ni_{1-x}O$) was synthesized on the top of the Ni skeletons (Figs. 3(a) and 3(b)). Both the visualization experiments and the simulation collectively revealed that gas bubbles typically invade in-plane pores when passing through the stochastic 3D structures of $C-Ni_{1-x}O/NF$, slowing down their escaping from the electrodes (Figs. 3(c)–3(e)). The extended residence time of bubbles trapped inside NF also increases the possibility of collision and coalescence with adjacent bubbles, resulting in larger bubble size and eventually covering more active sites as well as impeding the electrolyte transfer. In contrast, the periodic pores of 3D printed

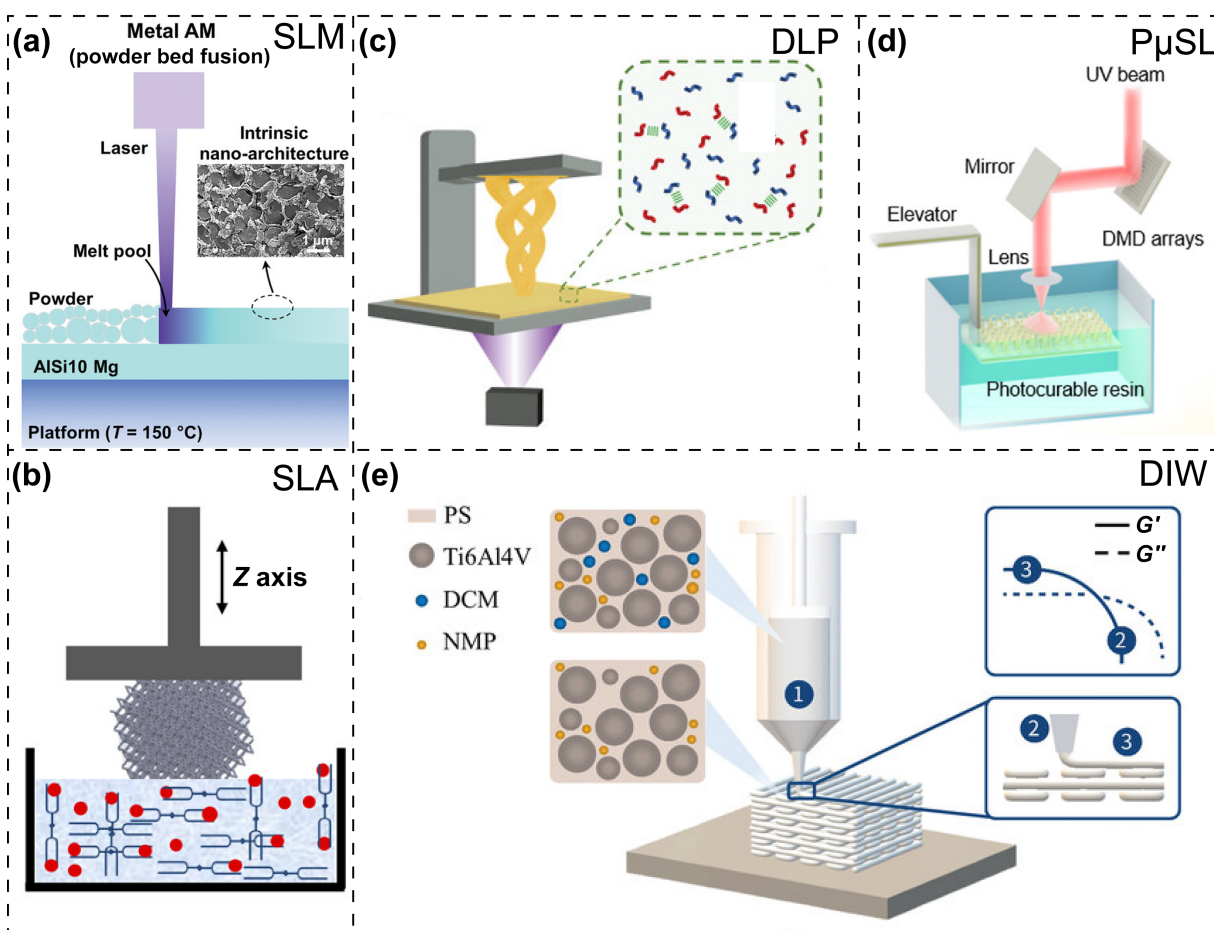


Figure 2 The schematics showing different 3D printing techniques. (a) SLM. Reproduced with permission from Ref. [41], © Ho, J. Y. et al. 2022. (b) SLA. Reproduced with permission from Ref. [42], © American Chemical Society 2022. (c) DLP. Reproduced with permission from Ref. [43], © Zhu, G. D. et al. 2024. (d) PμSL. Reproduced with permission from Ref. [44], © American Chemical Society 2021. (e) DIW 3D printing techniques. Reproduced with permission from Ref. [45], © Wiley-VCH GmbH 2024.

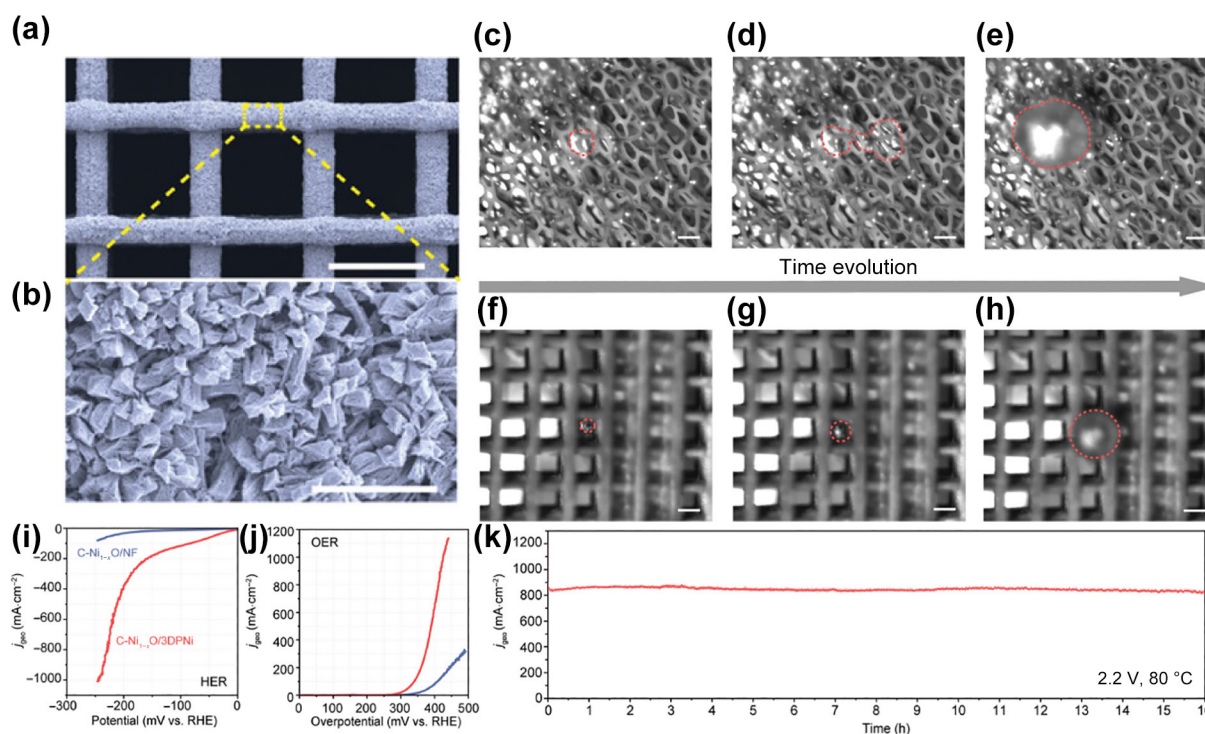


Figure 3 ((a) and (b)) Scanning electron microscopy (SEM) images of C-Ni_{1-x}O/3DPNi electrode at low (scale bar: 500 μ m) and high magnifications (scale bar: 4 μ m). The bubble transport through ((c)–(e)) C-Ni_{1-x}O/NF and ((f)–(h)) C-Ni_{1-x}O/3DPNi captured with top-view (scale bars: 500 μ m). (i) HER and (j) OER linear sweep voltammetry (LSV) plots of C-Ni_{1-x}O/NF and C-Ni_{1-x}O/3DPNi performed in 1.0 M KOH at the sweep rate of 0.1 mV·s⁻¹. (k) The stability test of C-Ni_{1-x}O/3DPNi||C-Ni_{1-x}O/3DPNi electrolyzer at 2.2 V in 1.0 M KOH electrolyte at 80 °C. Reproduced with permission from Ref. [10], © Wiley-VCH GmbH 2020.

electrode suppress the in-plane drainage process and facilitate bubble transport along the through-plane direction (Figs. 3(f)–3(h)), shortening the residence time of bubbles at the electrode. The gas bubbles with smaller size were also confirmed by the *operando* high-speed camera imaging. Thanks to the improved bubble traffic, the C-Ni_{1-x}O/3DPNi was endowed with higher electrolyte accessible surface area as well as enhanced mass transfer capabilities. When testing the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) activities in 1.0 M KOH (Figs. 3(i) and 3(j)), the C-Ni_{1-x}O/3DPNi was able to deliver the current density of 1000 mA·cm⁻² at 245 mV (HER) and 425 mV (OER), respectively. At the same current density, the C-Ni_{1-x}O/NF would require much higher overpotentials, validating the critical role of spatially ordered channels in mitigating bubble traffic. In an electrolyzer composed of the C-Ni_{1-x}O/3DPNi bifunctional electrodes, a current density of 850 mA·cm⁻² was maintained for at least 16 h (Fig. 3(k)).

Even though introducing periodic holes in the 3D printed scaffold enhances the bubble transport, how the geometry of holes impacts the bubble transport remained a question. Chen et al. [46] developed Ni sulfide (NiS₂) lattice with tunable pore geometry (circle, square, pentagon, and hexagon) by DLP 3D printing NiSO₄-containing resin scaffold, followed by a series of treatments, including sintering, hydrothermal growth of Ni(OH)₂, and subsequent vulcanization (Figs. 4(a)–4(d)). These pore geometries correspond to different edge numbers, with that of circular shape being considered at the maximum. The increased edge number decreases the contact area between bubble and the solid surface, thereby promoting bubble overcoming the adhesion force between the two and detaching at a smaller size. Their *in-situ* microscopic observation confirmed that bubble size decreases from 317 to 212 μ m and upward transport is facilitated (Fig. 4(e)) when

switching the hole geometry from square to circular shape. Multiphysics simulations (Fig. 4(f)) further showed much more rapid and uniform growth of bubbles in circular holes, implying faster attainment of the critical detachment state, higher release frequency, and smaller size at detachment. This pore geometry induced kinetic advantages, mitigating transport overpotential, yielding superior HER performances, such as 297 mV overpotential at 1000 mA·cm⁻² in 1 M KOH.

Beyond the design of macroscopic channels in 3D printed lattice, the surface morphological engineering at the nanoscale has also drawn attention to the community. As discussed earlier, the roughened surface reduces the contact area between bubble and the electrode, thereby decreasing the adhesion force for bubble detachment. When combining the periodic channel design with surface morphological optimization, the entire duration for bubble detachment and escape should be largely shortened. Following this design concept, Li and co-workers deposited Ni nanocones on the DIW 3D printed Ni lattice (Figs. 5(a) and 5(b)) [15]. It has been revealed that the nanocone arrays reduce triple-phase contact length and reorient adhesive forces, so that the adhesion can be weakened for facile detachment. *In-situ* high-speed imaging (Figs. 5(c)–5(h)) also showed that nanocone modification markedly reduced detachment time and size of gas bubbles, suppressed their coalescence, and conferred underwater super-aerophobicity of the electrode. The macro-nano dual-scale electrode architecture design boosted the electrode performances in both HER and OER, with the current density of about 900 mA·cm⁻² delivered at 2.45 V when assembling the electrodes into a single cell electrolyzer. Similarly, Feng et al. [47] electrodeposited NiFe-layered double hydroxide (LDH) nanosheets on the DIW 3D printed Ni substrate (NiFe-LDH/3DPNi) with periodic channels (Fig. 5(i)). In spite of the same

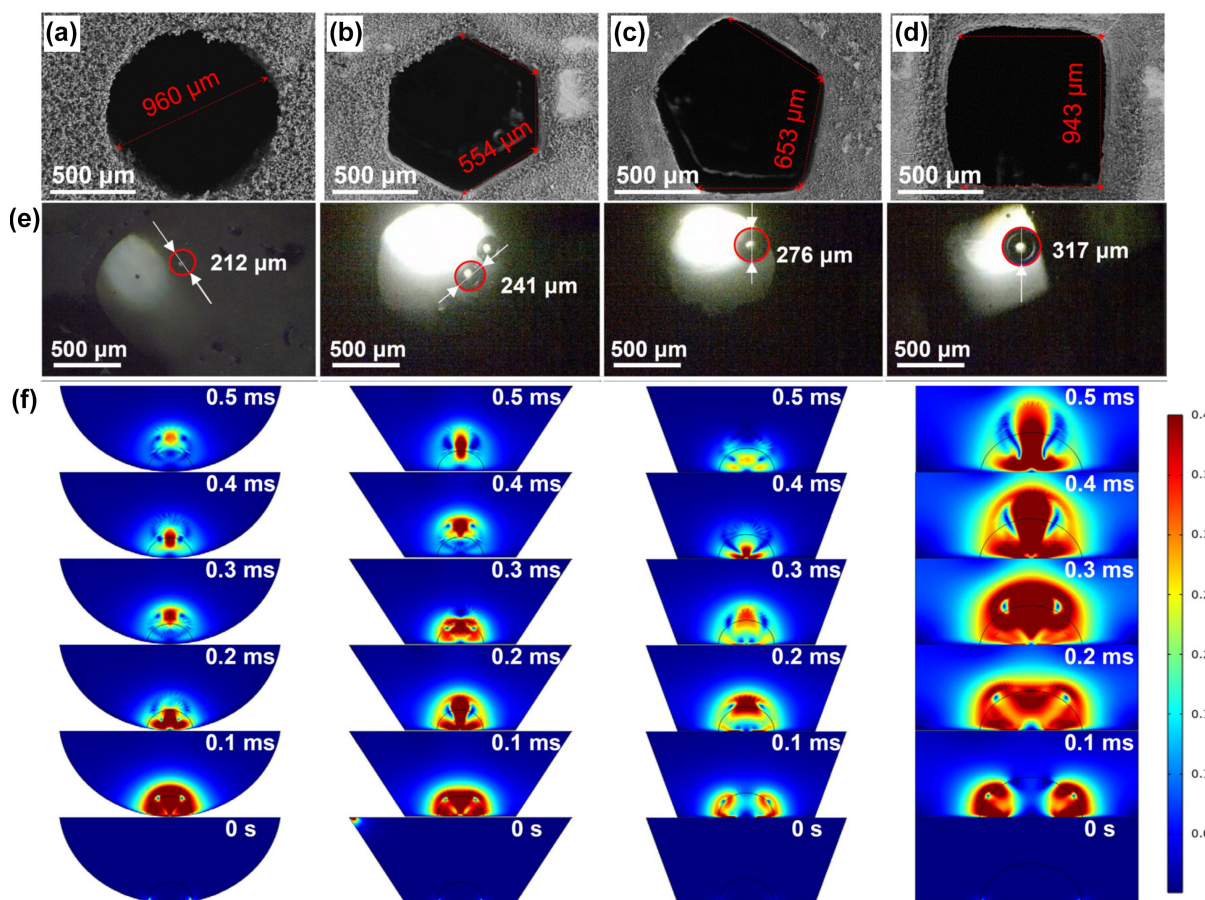


Figure 4 ((a)–(d)) SEM images of the 3D printed electrodes with different geometries after vulcanization. (e) The *in-situ* microscope imaging showed bubbles detached at these electrodes. (f) The simulation shows bubble growth velocity mapping in the pores with different geometries. Reproduced with permission from Ref. [46], © Chen, J. X. et al. 2024.

synthesis protocol for anchoring NiFe-LDH nanosheets on NF, the NiFe-LDH/3DPNi shows enhanced hydrophilicity and aerophobicity compared with those of the NiFe-LDH/NF. The observed difference is probably due to the intrinsic roughened surface of DIW 3D printed Ni and NiFe-LDH nanosheet arrays, which further increase the surface roughness. High-speed camera imaging reveals the mean bubble diameter for NiFe-LDH/3DPNi is 41.4 μm , less than half that of NiFe-LDH/NF (Figs. 5(j) and 5(k)). Meanwhile, the bubble release frequency tripled for NiFe-LDH/3DPNi vs. NiFe-LDH/NF, promoting the mass transfer of 3D printed electrode. NiFe-LDH/3DPNi thus required only 238 mV overpotential to achieve the OER current density of 100 $\text{mA}\cdot\text{cm}^{-2}$ (Fig. 5(l)) and remained stable in a stability test at 500 $\text{mA}\cdot\text{cm}^{-2}$ for more than 450 h.

During the SLM 3D printing, spherical particles are usually generated on the printed surface due to not completely melted powder or re-solidified spatter droplets. Adjusting the laser power density is helpful to tune the surface density of spherical particles, which is a strategy proposed by Wu et al. [48] to optimize the surface roughness of stainless steel for anchoring active species and rapid bubble detachment. The surface roughness was tuned from 3.4 to 7.9 μm without changing the macroscopic topological structure, forming a hierarchical structure with both macroscopic open channels and microscopically rough particles (Figs. 6(a) and 6(b)). NiFe-LDH nanosheets were then grown *in-situ* on the metal scaffold to form NiFe-LDH/3DP electrodes. High-speed camera

imaging showed that higher roughness yielded smaller but uniform bubbles and markedly higher detachment frequencies. The NF/3DP_{Ra=7.9} (NF here represents NiFe-LDH, and Ra means the roughness average in this work) electrode exhibited uniform micro-bubble streams and super-aerophobicity, whereas samples with lower surface roughness showed pronounced bubble coalescence and retention (Figs. 6(c)–6(f)). Consistent with the high-speed imaging results, the finite-element analysis (FEA) further elucidated the roughness effects on bubble detachment. Simulations revealed that increasing roughness reduces bubble-electrode contact stress and adhesion area, lowering the buoyancy threshold for bubble detachment (Fig. 6(g)). As a result, the NF/3DP_{Ra=7.9} only requires a 332 mV overpotential to drive the OER at an industrial current density of 1000 $\text{mA}\cdot\text{cm}^{-2}$, and maintains initial activity even after continuous operation for 1000 h at 500 $\text{mA}\cdot\text{cm}^{-2}$. These advances showcase the advantages of 3D printing and surface engineering for co-optimizing channel structures and bubble dynamics, providing an electrode design paradigm for high-rate water electrolysis.

The triply periodic minimal surface (TPMS) is a smooth, non-self-intersecting, and mathematically defined surface that is periodic in 3D space with mean curvature being zero at each point [49]. Typical TPMS structures (Fig. 7(a)) include the Gyroid, Fischer–Koch, and Schwarz structures, which are described by the following equations (Eqs. (3)–(5)), respectively [50]

$$t = \cos(kx) \sin(ky) + \cos(ky) \sin(kz) + \cos(kz) \sin(kx) \quad (3)$$

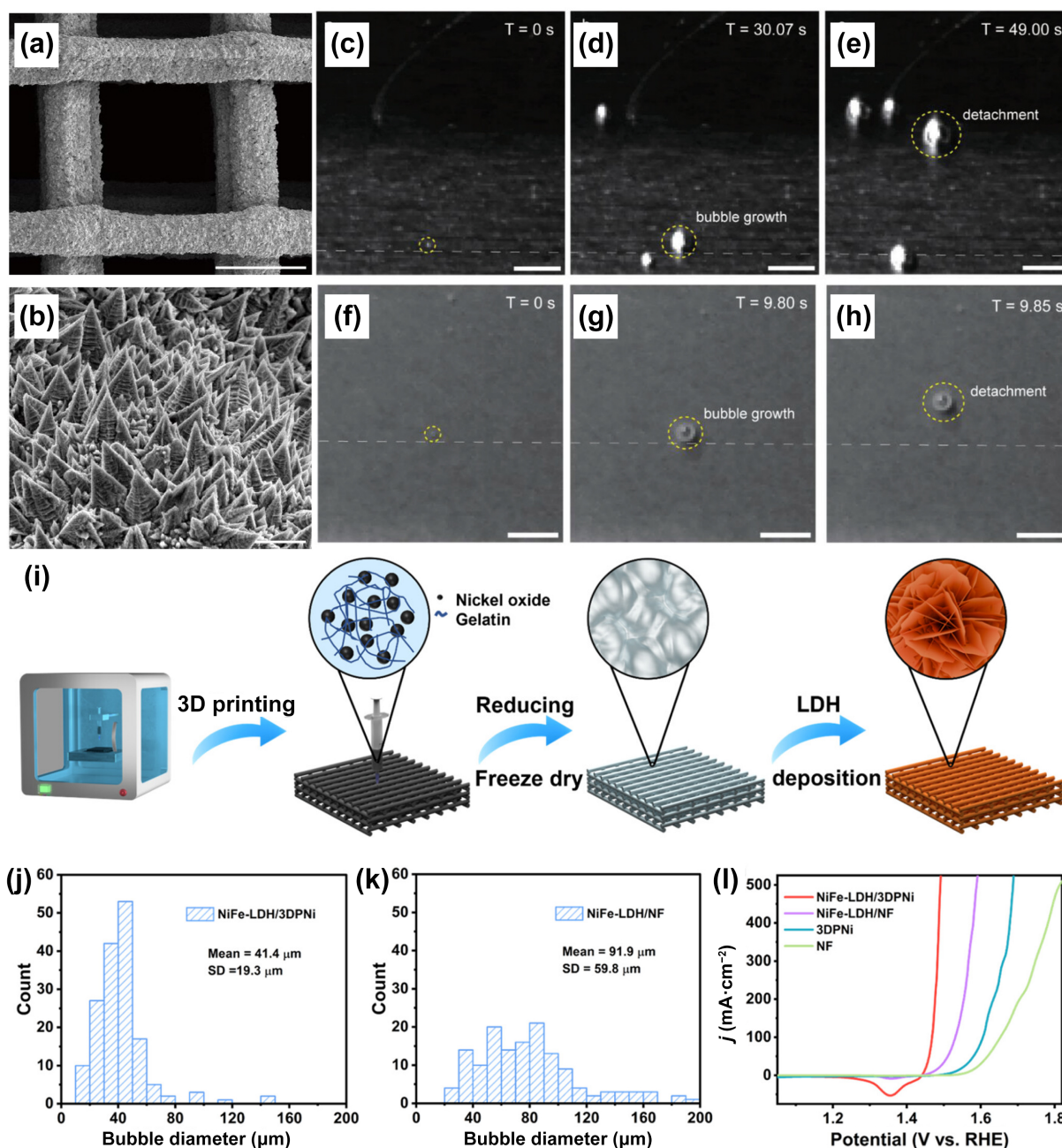


Figure 5 ((a) and (b)) SEM images of the 3D printed Ni substrate modified with Ni nanocones at low (scale bar: 300 μm) and high magnifications (scale bar: 1 μm). ((c)–(e)) and ((f)–(h)) High-speed camera imaging revealing the bubble evolution in HER before and after Ni nanocones modifications (scale bar: 500 μm). Reproduced with permission from Ref. [15], © Wiley-VCH GmbH 2023. (i) The schematic showing the synthesis of NiFe-LDH/3DPNi. ((j) and (k)) The bubble size distribution detached from NiFe-LDH/3DPNi and NiFe-LDH/NF. (l) The OER LSV plots. Reproduced with permission from Ref. [47], © American Chemical Society 2025.

$$t = \cos(2kx) \cos(kz) \sin(ky) + \cos(kx) \cos(2ky) \sin(kz) + \cos(ky) \cos(2kz) \sin(kx) \quad (4)$$

$$t = \sin(kz) \sin(kx) - 0.4 \sin(1.2ky) \cos(kz) \cos(kx) \quad (5)$$

where x , y , and z are the spatial coordinates, t is the isosurface threshold, and the geometric wave number (k) = $(2\pi)/L$, where L is the period length. The highly connected pore networks, as well as high specific surface area usually, endow TPMS architectures with improved mass transport capabilities. Rocha et al. [50] systematically investigated gas bubble escape from these three

typical TPMS electrodes for alkaline water electrolysis. The Schwarz structure exhibits different symmetry along one dimension, while the Gyroid and Fischer–Koch structures show the same symmetry in all directions. These symmetry differences vary the electrolyte flow behavior, which can affect the gas evacuation. For example, their computational fluid dynamics simulations (Figs. 7(b)–7(d)) revealed that the lateral mixing was largely suppressed when the electrolyte was forced to flow through the porous Schwarz TPMS electrode. In comparison, the uniform symmetry of Gyroid and Fischer–Koch structures results in dominant lateral mixing in the electrolyte flow-through model, which promotes bubble coalescence and hinders the mass transfer. Under conditions of the

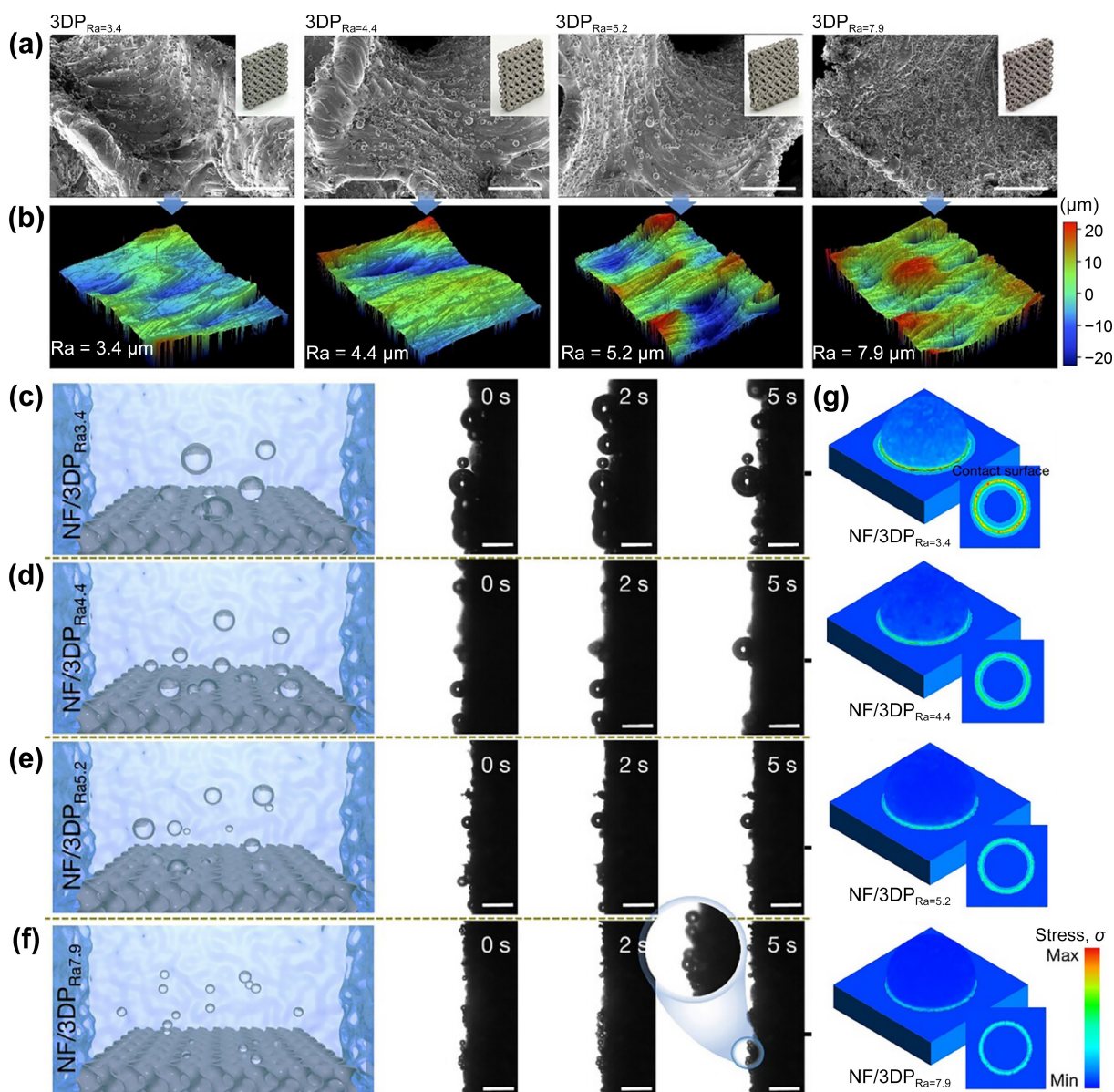


Figure 6 ((a) and (b)) The SLM 3D printed electrodes and surface morphologies with relevant surface roughness (scale bar: 500 μm). ((c)–(f)) The schematics and high-speed camera imaging showing bubble growth and detachment behaviors at 10 $\text{mA}\cdot\text{cm}^{-2}$ (scale bar: 200 μm). (g) The bubble adhesion force simulation on electrodes with different surface roughness. Reproduced with permission from Ref. [48], © Wiley-VCH GmbH 2025.

same porosity (61%) and surface area (32 cm^2), the permeability of the Schwarz structure is 0.08 m^2 , which is approximately three times that of the Gyroid (0.026 m^2) and Fischer–Koch (0.027 m^2). Meanwhile, the friction factor of the Schwarz is only 1/4 to 1/5 of the other two, indicating that its longitudinal flow channels significantly reduce the flow resistance and probability of bubble coalescence. However, it should be noted that the performance ranking depends on electrode symmetry, flow regime (forced flow vs. natural convection), and ECSA. Under forced flow, Schwarz electrode outperforms at lower ECSA of 100 cm^2 (Fig. 7(e)), leveraging its longitudinal channeling for higher permeability and reduced friction factor, suppressed lateral mixing, and more efficient bubble removal. However, at higher ECSA of 175 cm^2 , Gyroid reverses to the lead (Fig. 7(f)), as its multi-directional and interconnected pore network better accommodates the increased bubble generation density in its finer strut configurations,

facilitating detachment and electrolyte replenishment. Under natural convection (i.e., removing the forced electrolyte flow), Schwarz shows no clear performance difference compared with that of Gyroid at the ECSA of 100 cm^2 (Fig. 7(g)), but increasing the ECSA to 175 cm^2 yields substantial improvement exclusively for Gyroid (Fig. 7(h)) due to effective buoyancy-driven bubble detachment within its isotropic network. In contrast, the Schwarz exhibits bubble entrapment, confirming that the excess ECSA becomes inaccessible without forced flow. Thus, Schwarz leverages its flow channeling benefits most effectively in coarser structures (lower ECSA) under forced flow, while the isotropic design of Gyroid dominates in denser configurations (higher ECSA), particularly exploiting buoyancy under natural convection. Xun et al. [51] adopted a three-step strategy to realize DLP 3D printed Gyroid monolithic Ni–Mo electrode for alkaline HER at high current densities. The slurry containing $\text{Ni}(\text{OH})_2$, MoO_3 , and

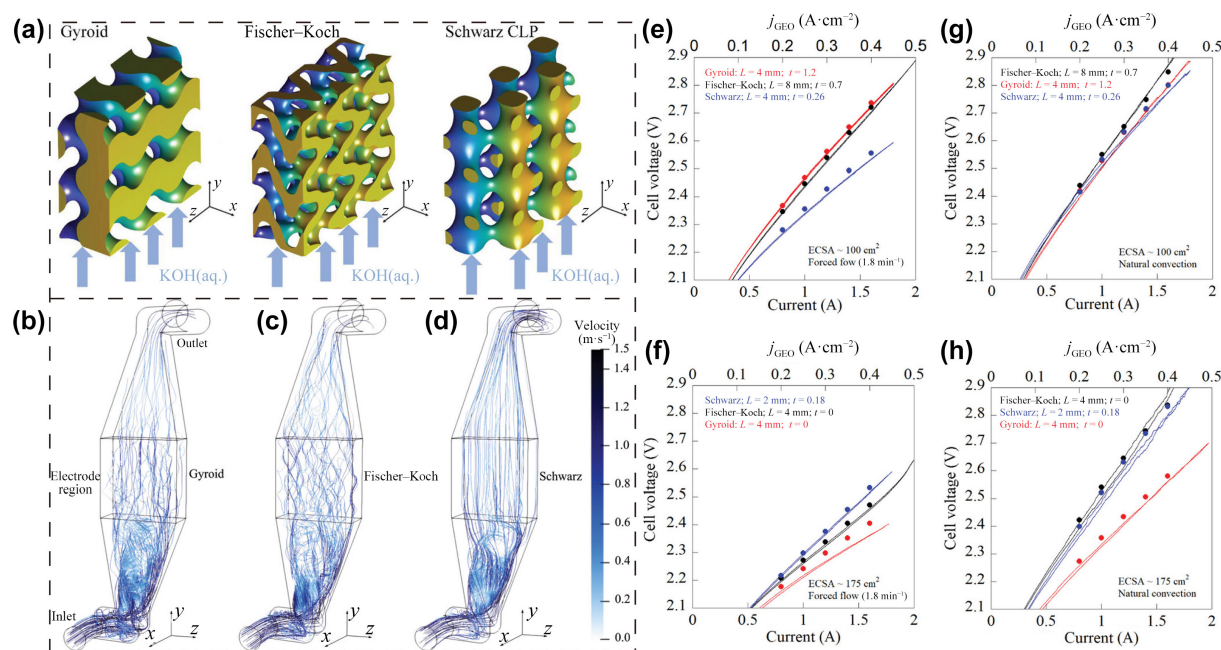


Figure 7 (a) The typical TPMS structures. (b)–(d) The simulation shows different flow patterns for Gyroid, Fischer–Koch, and Schwarz structures. The relationship of voltage and electrical current/current density for TPMS structures when the ECSA is 100 and 175 cm², under ((e) and (f)) forced flow and ((g) and (h)) natural convection conditions. Reproduced with permission from Ref. [50], © Rocha, F. et al. 2022.

Genesis resin was mixed and printed at room temperature under UV light irradiation, followed by the high-temperature sintering treatment. The as-sintered NiMo phase was found to show desirable water dissociation activity, while the sintering temperature at 900 °C modulates the porosity for the highest ECSA. Compared with wood-pile, octet truss, and honeycomb structures, the Ni-Mo electrodes with Gyroid structure show lower overpotential when delivering higher current densities (1500 mA·cm⁻² at 325 mV).

Schwarz diamond (SD) architecture features highly ordered porosity with uniform apertures as well as wide pore size distribution in 3D space, outperforming the NF with irregular pores and the Ni mesh (NM) with low site availability for anchoring active sites. The SLM 3D printed SD skeleton (Figs. 8(a) and 8(b)) was used as substrate for water electrolysis catalysts growth in a recent work [52], with NiMoFeO_x (NMF) and MoNi₄-MoO₂ (MNO) coated on the SD as OER and HER electrodes, respectively. *In-situ* bubble imaging and single-frequency impedance-time were performed for the electrolyzers employing catalysts supported on different substrates (Figs. 8(c)–8(f)). The results (Fig. 8(c)) confirmed the efficient transport paths for both electrolyte and bubbles along the parallel and ordered channels of the SD, enabling rapid bubble detachment and reducing site blockage. By contrast, NF retained large bubbles with erratic release directions, whereas stacked NM induces turbulent electrolyte flow that slows down mass transfer (Figs. 8(d) and 8(e)). The anion exchange membrane (AEM) water electrolyzer utilizing SD-supported catalysts achieved a current density of 1 A·cm⁻² at 1.74 V (80 °C) (Fig. 8(g)), outperforming conventional NF and NM based electrolyzers under the same testing conditions and demonstrating durable operation for 1000 h (Fig. 8(h)).

3.2 Functionally graded and directional architectures for bubble management

Rather than a single and uniform topology, the designs of spatial gradients or directional architectures add extra degree of freedom. When combined with selective catalyst deposition, graded

architectures concentrate active sites where they are most needed while routing bubbles along low-resistance paths, minimizing residence time and co-mixing, so that a local trade-off between activity and two-phase transport can be achieved. This strategy is especially valuable in membrane-less cells where ionic path length and gas management must be optimized simultaneously. As an example, Huang et al. [12] compared the bubble behaviors at Ni gas diffusion layers (GDL) with different grid sizes. The wood-pile structured GDL was printed by DIW technique with NiO-based ink, followed by annealing treatment to remove polymer binder and reduce NiO into metallic Ni. The grid size of the GDL is controlled by varying the center-to-center spacing between the adjacent filaments (Figs. 9(a)–9(e)). It has been revealed that the smaller grid size can enhance catalyst utilization, yet the adhesive force between bubble and GDL can be increased due to the larger bubble contact area. The GDL with larger grid size is able to reduce flow resistance and bubble evacuation, but the catalyst utilization will be very low, which is detrimental to the pure-water-fed AEM water electrolysis. The GDL with graded pore structure was prepared by printing multiple grid size layers, with smaller pores adjacent to the NiFe catalyst layer and progressively larger pores toward the flow field (Figs. 9(f) and 9(g)). The electrolyzer using the GDL with 240 and 550 μm hybrid grid sizes shows the most desired pure-water-fed AEM water electrolysis performances, and the current density of 2 A·cm⁻² can be achieved at a low voltage of 1.95 V (Fig. 9(h)). The quantitative link between bubble detachment and grid size established in this work provided important instructions in the GDL design and the regulation of two-phase flow within zero-gap electrolyzers. In addition to GDL, the graded pore design has also been directly used in developing electrodes. By using DLP 3D printing and subsequent annealing treatment, Fu et al. [13] incorporated graded porosity in Gyroid-like structures (denoted as 3DP Ni-G) and compared the bubble behaviors with those of periodic ordered Gyroid architectures with either smaller (3DP Ni-S) or larger pores (3DP Ni-L) (Figs. 10(a)–

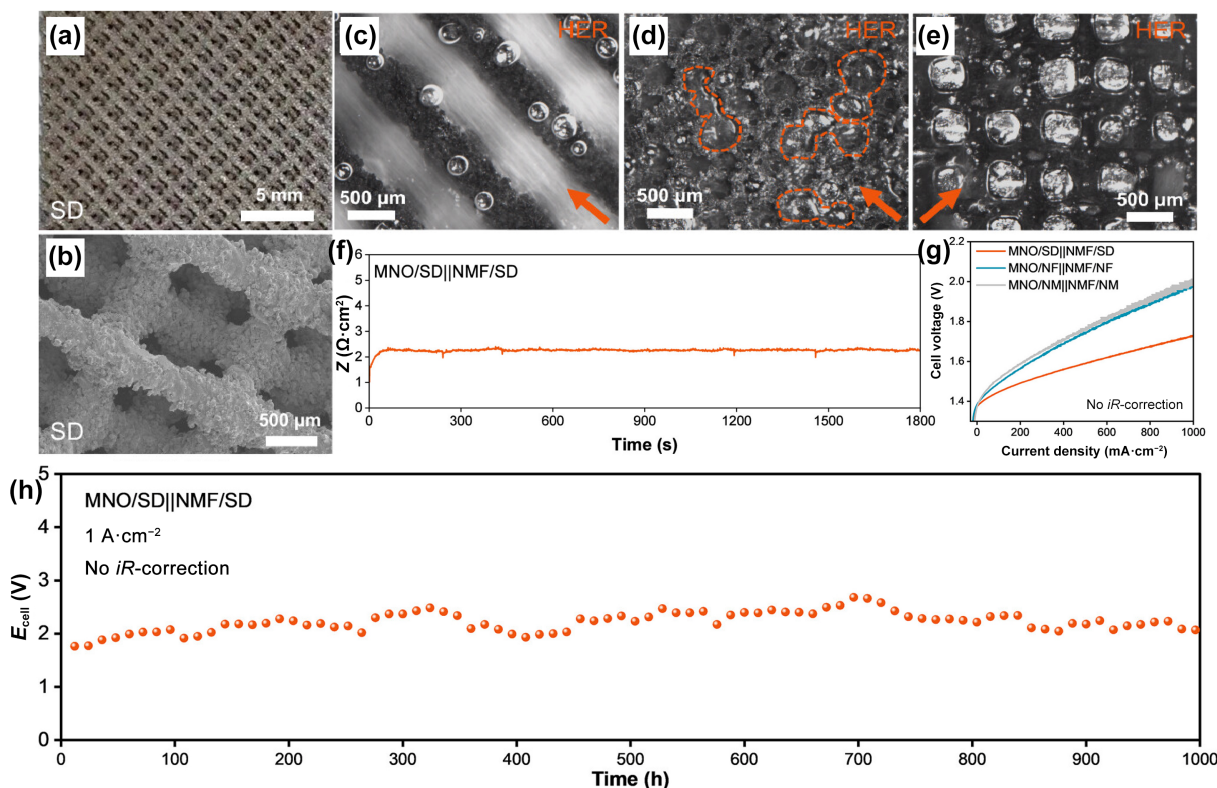


Figure 8 ((a) and (b)) The SD substrate and its SEM image. The high-speed camera imaging the HER electrode for the electrolyzers of ((c)–(e)) MoNi₄-MoO₃/SD||NiMoFeO₄/SD, MoNi₄-MoO₃/NF||NiMoFeO₄/NF, and MoNi₄-MoO₃/NM||NiMoFeO₄/NM operated at 1 A·cm⁻². (f) The single-frequency impedance vs. time for MoNi₄-MoO₃/SD||NiMoFeO₄/SD run at 0.5 A·cm⁻². (g) The LSV plots for the different electrolyzers. (h) The stability test of MoNi₄-MoO₃/SD||NiMoFeO₄/SD at 1 A·cm⁻². Reproduced with permission from Ref. [52], © American Chemical Society 2025.

10(c)). The small pores on one side of the 3DP Ni-G increase surface area and active site density, and large pores on the other side can reduce bubble resistance. Through employing different etchants, such as RuCl₃ and FeCl₃, the Ru-Ni(OH)₂ and Fe-Ni(OH)₂ nanolayers can be grown on the printed scaffolds to serve as HER and OER catalysts, respectively (Figs. 10(d) and 10(e)). High-speed camera imaging tracked the bubble transport and release duration formed in the Janus porous structures of the 3DP Ni-G electrodes. The gas bubble only takes 83.3 ms to escape from the surface of larger pore side (Fig. 10(f)), while it is 133.3 ms for bubble to release from the small pore side (Fig. 10(g)). Theoretical analysis of the pressure distribution reveals the pronounced pressure drop within the 3DP Ni-G (Fig. 10(h)), which is in sharp comparison with the gradual pressure drop in 3DP Ni-L and 3DP Ni-S. This significant internal pressure drop is one important reason to accelerate bubble escape. As confirmed by the bubble velocity distribution (Fig. 10(i)), the 3DP Ni-G corresponds to the highest mean bubble velocity of 10.1 μm·s⁻¹, which is more than twice that of 3DP Ni-L and 3DP Ni-S, suggesting its higher mass transfer efficiency and faster bubble evacuation. The Janus gradient porosity enabled controllable bubble dynamics and highly stable performance in water electrolysis. The 3DP Ni-G electrodes show excellent activity with an overpotential of 98 mV for HER (Ru-Ni(OH)₂) and 343 mV for OER (Fe-Ni(OH)₂) at the current density of 500 mA·cm⁻² in 1 M KOH (Figs. 10(j) and 10(k)). The electrolyzer using these 3DP Ni-G electrodes was found to show 2100 h stability at 500 mA·cm⁻² without observable decay at the voltage of 1.638 V (Fig. 10(l)).

Inspired by the capillaries of plants delivering the water and nutrients, vertically aligned graphene-based capillary arrays with

side pores were realized by Z axis controllable DLP printing (Fig. 11(a)) [53]. The design was believed to enable co-management of bubble release and electrolyte feeding during electrolysis (Figs. 11(b) and 11(c)). This scaffold was uniformly anchored with CoNi carbonate hydroxides (CoNiCH) nanoneedles (with length of 5 μm) through hydrothermal method to enhance activity, and the side pore of about 30 μm in diameter can be clearly seen on the capillary arrays (around 80 μm in diameter) even after the catalysts coating (Figs. 11(d)–11(g)). The *in-situ* optical microscopy unveiled the bubble release and water supply behaviors. Specifically, the bubbles consistently exited the main tube arrays rapidly while electrolyte was continuously replenished through side pores, yielding a stable bubble escape and water supply mode with no evident bubble retention. This should be rationalized by the value of additional pressure (*P*), which is determined by the following Eq. (6)

$$P = \frac{2\gamma}{r} \quad (6)$$

The side pore is small in size compared with that of the tube arrays, leading to higher additional pressure of 6.5 kPa that helps push water into the tube arrays through these side pores. The COMSOL studies confirmed a high bubble velocity of 1.5 m·s⁻¹, which suggests that the dynamic balance of gas transport and water renewal can be achieved in this structure (Figs. 11(h) and 11(i)). The assembled electrolyzer can reach a water electrolysis current density of 10 mA·cm⁻² at 1.51 V and maintain stability in a 60 h test at 30 mA·cm⁻² without significant decay.

Membrane-less water electrolysis represents a low-cost strategy in hydrogen generation, yet many limitations remain in enhancing

the performance. Maintaining a high concentration of reactant ions and ensuring rapid ionic diffusion between electrodes during high-rate electrolysis are two of these challenges. Ren et al. [14] proposed a membrane-less water electrolyzer by deploying interpenetrating

Gyroid electrodes (3DIG) architecture through SLA 3D printing combined with Ni electroless plating. The two independent yet spatially approaching Ni frameworks enable geometric interpenetration of anode and cathode and ultrashort ionic

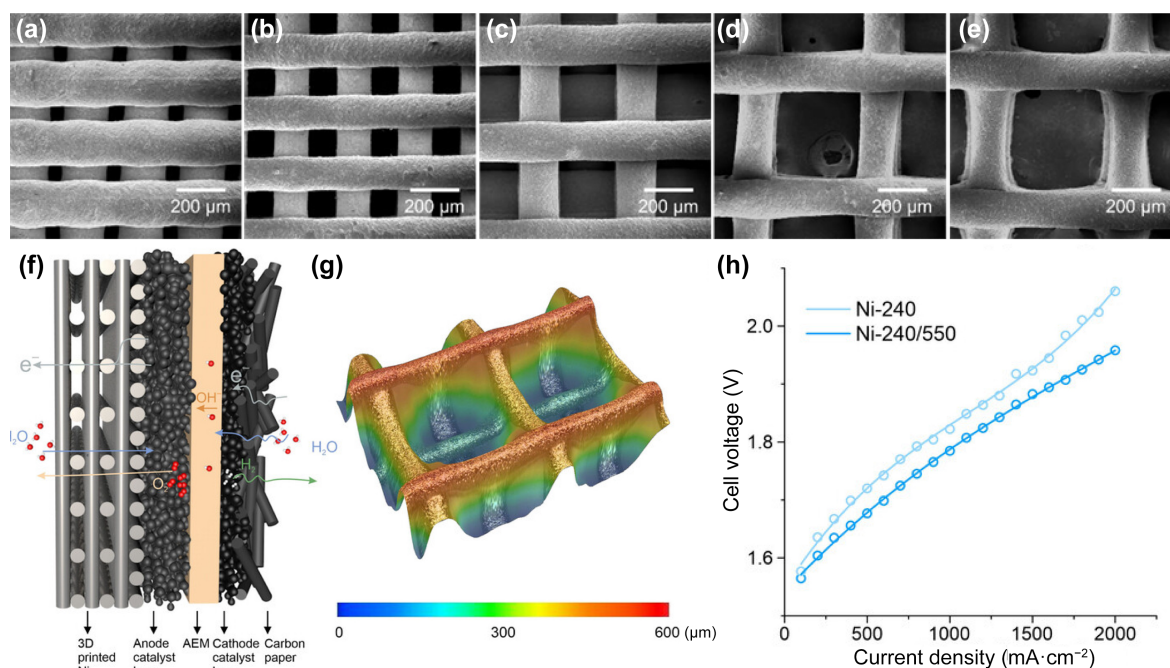


Figure 9 ((a)–(e)) The SEM images of 3D printed Ni with different center-to-center spacings. (f) The schematic showing the major components of AEM water electrolyzer. (g) The Ni-240/550 (240 and 550 refer to the grid sizes of the hybrid Ni GDL in μm) optical structure. (h) Pure-water-fed AEM water electrolysis performance comparisons of the electrolyzer employing Ni-240/550 and Ni-240. Reproduced with permission from Ref. [12], © Wiley-VCH GmbH 2023.

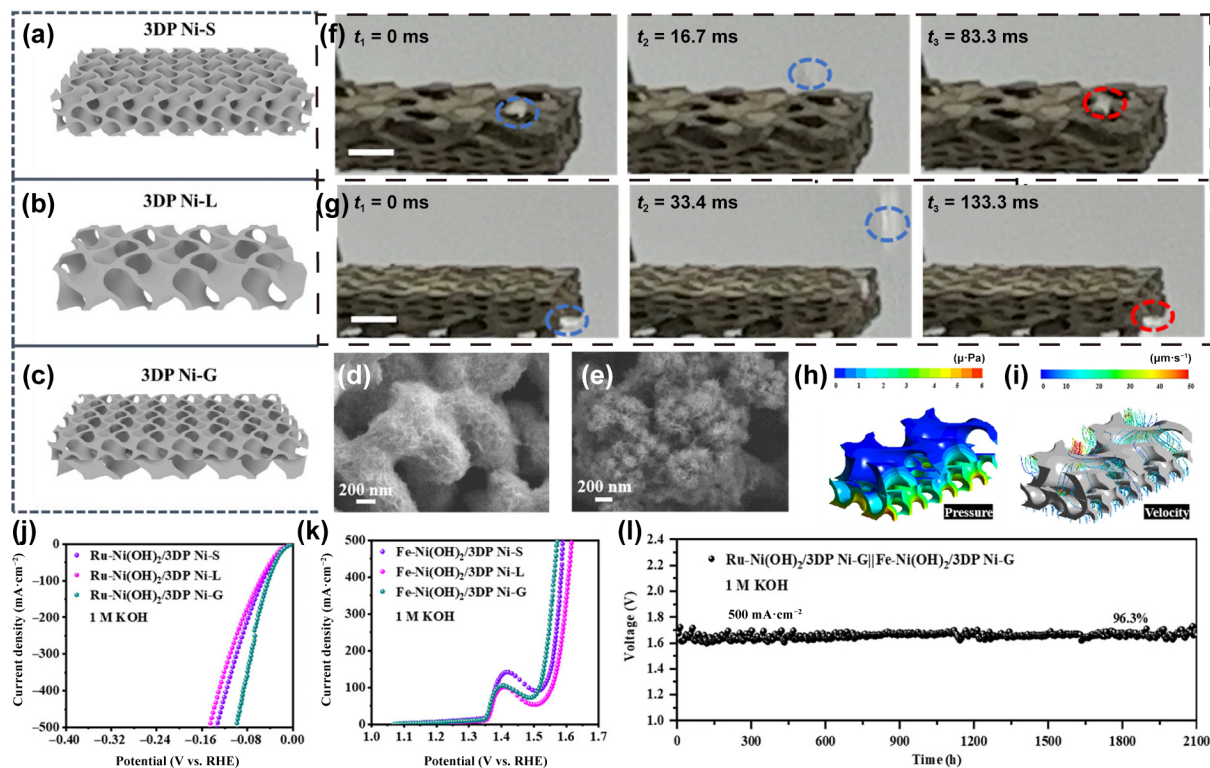


Figure 10 ((a)–(c)) The structures of 3DP Ni-S, 3DP Ni-L, and 3DP Ni-G. ((d) and (e)) SEM images showing the morphologies of Ru-Ni(OH)₂ and Fe-Ni(OH)₂. ((f) and (g)) The bubble release behaviors of Fe-Ni(OH)₂/3DP Ni-G with large and small pores facing upward, with the scale bar of 2 mm. ((h) and (i)) The pressure and bubble velocity distribution in the Fe-Ni(OH)₂/3DP Ni-G. ((j) and (k)) LSV plots of HER and OER. (l) The stability test of Ru-Ni(OH)₂/3DP Ni-G||Fe-Ni(OH)₂/3DP Ni-G electrolyzer at 500 mA·cm⁻² in 1 M KOH. Reproduced with permission from Ref. [13], © Fu, G. W. et al. 2023.

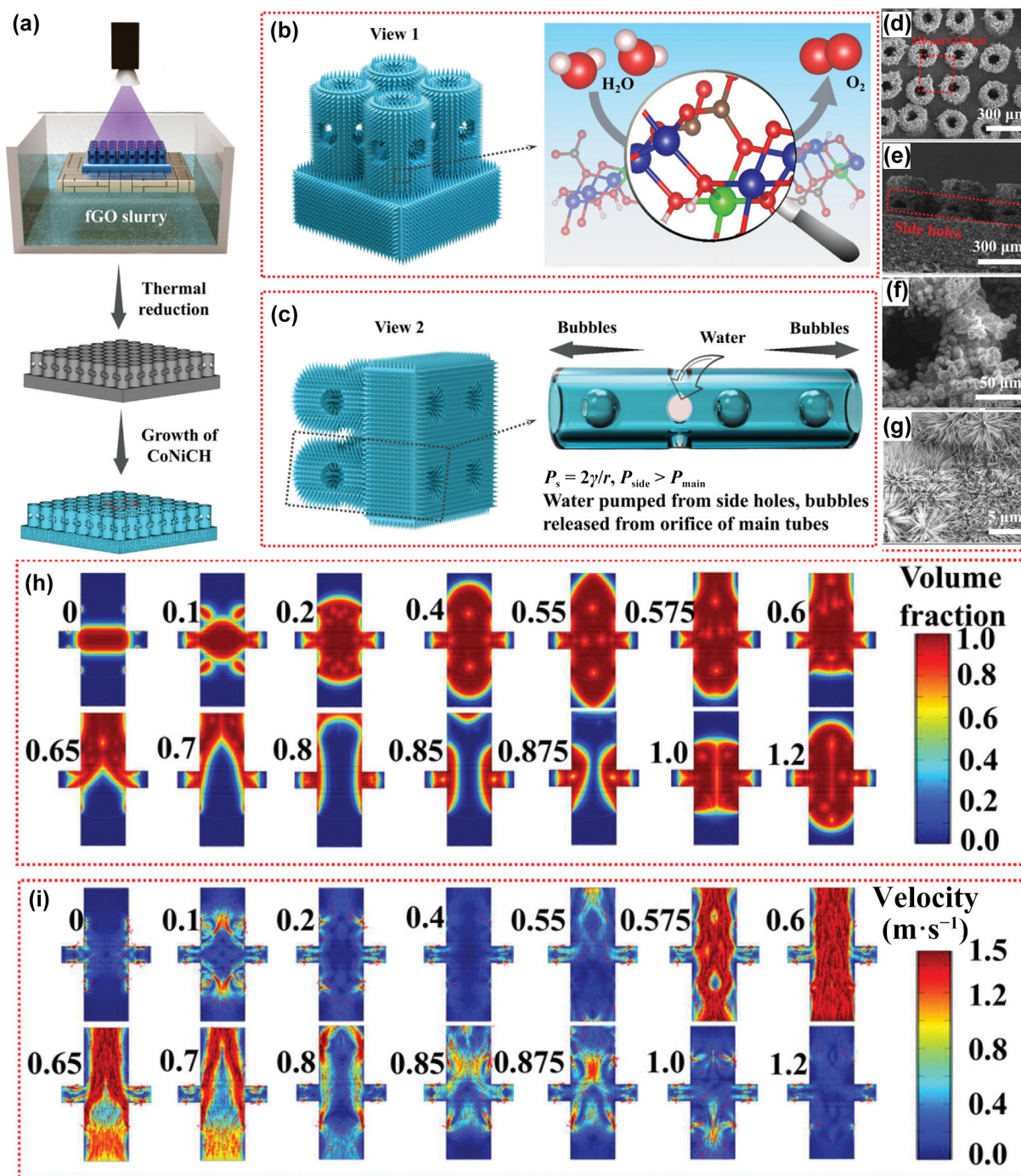


Figure 11 (a) The schematic showing the DLP 3D printing and catalyst coating. ((b) and (c)) The pores for pumping water and bubble release from different angles. ((d)–(g)) SEM images of the morphologies of catalysts-coated electrode. ((h) and (i)) The COMSOL simulation showing the volume ratio of water (blue)/O₂ (red) and velocity of O₂ release/water supply in two-phase transport. Reproduced with permission from Ref. [53], © Zeng, T. B. et al. 2023.

diffusion paths. Compared with conventional electrolyzer with parallel stacked electrodes (3DG), the 3DIG architecture significantly reduces interelectrode spacing, improves ion transport uniformity and electrolyte utilization, and maintains continuous electrolyte supply within the open channels. Further electrolysis measurements show that the 3DIG electrolyzer requires a voltage of 2.85 V to deliver 1000 mA·cm⁻², superior to the 3DG electrolyzer tested under the same conditions. Stability testing was performed at 2.4 V, and a relatively stable current density of around 350 mA·cm⁻² can be maintained for 100 h, validating the robustness of 3DIG

electrolyzer. In addition to rapid ionic transport, another critical challenge of membrane-less electrolysis is the gas mixing, which poses difficulties in purifying hydrogen. Even though larger inter-electrode spacing can mitigate the gas mixing, the Ohmic resistance of the electrolyzer can increase significantly. Yu et al. [54] reported a biomimetic electrode to address the gas mixing in membrane-less electrolyzer by structural and surface wettability engineering. They proposed tilted micro-cone arrays with “slippery aerophobic” surface to guide bubbles unidirectionally along the micro-cone surface, thereby preventing the premature bubble detachment and

cross-mixing. The μ SL 3D printing technique was used to realize the aforementioned structures, with intervals between these micron-cones and bottom radius controlled to be 200 and 150 μm , respectively. The tilting angle can be flexibly adjusted between 10° and 60° . Multiple-step deposition was performed to have Ni-P responsible for electrical conducting, Cu middle layer for tuning surface roughness and wettability, and the outmost Pt or Ir coating as the active center for HER or OER. In order to realize the unidirectional “rolling-to-detachment” trajectory of gas bubbles, authors established a synergistic tuning of surface wettability and micro-cone tilting angle. The controlled Cu deposition enables moderate vertical adhesion and prevents the premature bubble detachment. Meanwhile, the low lateral adhesion realizes the bubble rolling. Changing the tilting angle can influence the driving force (Laplace pressure combined with buoyancy) as well as the resistance to gas bubble motion, and the optimized angle was found to be 50° at which the bubble transports faster and more smoothly. *In-situ* microscopy revealed that bubbles migrated upward unidirectionally along the cones, achieving spontaneous gas separation with purity more than 99.99% at a 1.5 mm electrode gap, demonstrating a clear advantage over other membrane-less electrolyzers using conventional superaerophobic electrodes.

4 Conclusions and outlook

In conclusion, this review has underscored the transformative potential of 3D printing in engineering electrodes for bubble management in high-rate water electrolysis. The relevant advances to date show two complementary architectural strategies that reliably improve bubble dynamics. The periodic ordered lattices, including these mathematically defined topologies (for example, the TPMS and its variants), provide predictable pathways that guide bubbles through aligned pores or longitudinal channels, so that the lateral drainage/coalescence can be suppressed and the bubble escape routes can be shortened. The local pore geometry and curvature are important parameters as well to reduce the contact area and promote bubble release frequencies. Functionally graded and directional designs (such as Janus porosities, tilted micro-cone arrays) introduce spatial heterogeneity to optimize the trade-offs between ECSA and bubble/ionic transport. For example, the fine pores adjacent to catalyst layers maintain ionic contact and ECSA, while progressively coarser pores toward the flow field reduce flow resistance and facilitate the bubble evacuation in AEM water electrolyzers. When combining these macroscopic architecture design strategies with nanoscale surface engineering, the bubble dynamics and mass transfer can be promoted. Several studies exemplify the benefits of combining these macroscopic architecture design strategies with nanoscale surface engineering. For instance, electrodepositing Ni nanocones [15] or NiFe-LDH nanosheets [47] on DIW printed Ni lattices with periodic channels, or tuning surface roughness of porous stainless steel via adjusting SLM parameters and growing NiFe-LDH nanosheets [48], can reduce the gas-liquid-solid (i.e., the catalysts) triple-phase contact length and adhesion forces between bubble and electrode, enabling smaller bubble detachment size and faster release frequencies. The periodic macroscopic open channels of the printed scaffolds enhance the evacuation of detached gas bubbles and improve reactant supply to the active sites. Consequently, mass transport overpotentials can be decreased at industrially relevant current densities. In addition, the multi-scale design strategy also minimizes the bubble-induced

mechanical stress and catalyst delamination, which helps improve the electrode stability in long-term chronopotentiometry or chronoamperometry tests. However, the systematic post-stability analyses of the catalysts still remain limited, hindering the comprehensive understanding of the degradation mechanisms of the potential electrodes.

Despite these encouraging advances, 3D printed electrodes optimized for bubble management remain in their early stages of development. Significant gaps persist on the path to extensive and large-scale deployment in industry, and many of them stem from inherent limitations of the current 3D printing technologies. For instance, DIW and DLP techniques have been routinely employed in manufacturing electrodes for water electrolysis, yet both methods frequently necessitate complicated and time-intensive post-printing treatments for electrical conductivity and mechanical strength enhancement needed for efficient and long-term operation. In addition, the impact of these post-printing treatments on electrode performance is evident in the studies, where parameters like annealing temperature and atmosphere require attention to optimize properties. For example, sintering the DLP printed mixture of $\text{Ni}(\text{OH})_2$, MoO_3 , and Genesis resin in Ref. [51] at 900°C can remove the electrical insulating Genesis resin and drive the reduction and solid-state reaction to form NiMo alloy in reducing atmosphere. Further increasing the sintering temperature to 1500°C enlarges the secondary pores and reduces ECSA. Similarly, DLP printed NiSO_4 and resin mixture that were calcined in air at up to 1000°C to both remove this resin and convert the Ni salt to oxides [46]. In a subsequent treatment in Ar/H_2 , the NiO was then reduced to metallic Ni substrates so that high electrical conductivity was obtained. The annealing at high temperature and reducing ambiance like H_2 for Ni scaffolds from DIW [10] was also routinely adopted to remove polymer binder, restore electrical conductivity, and enhance the mechanical strength. These examples illustrate that the careful control of these post-printing treatment parameters is critical, but also further increases the time investment in electrode preparation. In contrast, SLM can realize the metallic scaffold in a single build step, but the associated costs and high-purity powders introduce practical barriers. The printing resolutions of most mainstream 3D printing techniques are typically limited to hundreds of microns, necessitating subsequent surface nanostructuring to anchor active species and achieve sufficiently high ECSA. Although certain VP 3D printing technique variants, such as μ SL and two-photon lithography (TPL), can attain micron or sub-micron level resolution, their build volumes are severely constrained. The TPL, being a point-by-point writing process, inherently suffers from low throughput, further compounded by the high costs of precision optics and femtosecond lasers. For the deployment of megawatt-scale water electrolyzer stacks, the field urgently requires breakthroughs in one-step and low-cost rapid printing methodologies capable of producing scalable and conductive nanoscale scaffolds that meet the stringent standards of nanoelectrodes manufacturing.

The material systems employed in 3D printed electrodes for water electrolysis likewise remain somewhat constrained. As discussed in Section 3, substrates are typically Ni [10, 15], alloys (like NiMo, stainless steel) [48, 51] or graphene [53], while the catalytically active layers, such as Ni oxides [10], sulfides [46], hydroxides [13], NiFe-LDH [47, 48], and binary metallic carbonate hydroxides [53], are grown post-printing by strategies, such as wet chemical methods. Recent efforts have also broadened the printable

substrates. For example, the DIW printed Cu-graphene composites [55], and SLM printed Ti alloy lattices coated with binary metallic carbonate hydroxides [56, 57] demonstrate the routes to non-Ni-based materials systems in water electrolysis. However, the majority of current reports that optimize architectures for bubble mitigation are primarily about Ni-based materials. Expanding the range of printable and water electrolysis-relevant materials (such as nitrides, phosphides, or doped materials) with tailored wettability would be essential to integrate active centers during printing, saving time and costs associated with additional catalyst growth and enabling more direct control over bubble dynamics.

Bubble behaviors are conventionally investigated in three-electrode configurations under natural convection using high-speed camera imaging. While this approach yields direct insights into bubble dynamics and electrode wettability, it is important to recognize that bubble behaviors may differ substantially under natural convection vs. forced flow in an electrolyzer, even for identical 3D electrode geometries. Gas bubble detachment and transport behaviors can be highly influenced by the shear forces induced by forced electrolyte flow in realistic electrolyzers. Performing *operando* visualization in customized optical electrolytic cells under forced flow conditions would be more informative for elucidating realistic bubble dynamics. However, under high-rate electrolysis conditions, the intense bubble generation and their complex interactions can obscure clear tracking during *operando* visualization, unlike the more controlled environments of three-electrode setups under natural convection. Furthermore, gas bubble behaviors within the interior pores of 3D printed electrode cannot be directly observed due to the optical opacity and structural complexity. Conventional high-speed camera imaging is effective only for observing surface bubbles but fails to provide useful insights into bubble motion within the internal pores of the 3D printed electrodes, especially given the opaque nature of the 3D printed electrode materials. Intense bubble generation under forced flow also makes the high-speed camera imaging inadequate for resolving and analyzing gas bubbles. In order to better probe gas bubbles under forced flow and deep within the 3D printed electrodes at high-rate conditions, some emerging techniques, such as neutron radiography and *in-situ* fiber-optic sensing, could be alternatives for these electrodes in water electrolysis. Neutrons are strongly attenuated by ^1H in electrolyte, while they can penetrate easily through most metal plates as well as gas bubbles. This advantage has made the neutron radiography one powerful non-destructive technique [58] for imaging the gas bubbles inside the porous electrodes. In addition, the neutron radiography can image gas bubbles at high current densities, such as $9\text{ A}\cdot\text{cm}^{-2}$ in a previous report [59], whereas at such high current densities, the high-speed camera imaging is difficult to capture the bubble behaviors due to the vigorous bubble interactions. However, the spatial resolution of neutron imaging [60] can limit its capabilities in resolving bubbles at earlier growth stages. The requirement of neutron sources and difficult access to these facilities also restricts the extensive studies of bubble behaviors within different 3D printed electrodes using this technique. Very recently, *in-situ* fiber-optic sensing has been developed in monitoring gas bubbles in electrolyzers [61, 62]. This technique detects bubble behaviors by sensing changes in surface-plasmon resonance caused by gas generation at the interface between fiber and electrode, and gas bubbles as small as $79\text{ }\mu\text{m}$ were found to be resolved [61]. Moreover, the easy access and simple integration of this setup further endow it with strong values as an

operando technique for bubble monitoring within 3D printed electrodes.

Last but not least, while bubble behaviors are pivotal in high-rate electrolysis, they are only relevant to the extrinsic activity of electrodes. The study of intrinsic activity of active species is equally important when analyzing the performance of 3D printed electrodes. Therefore, multi-scale experimental and computational studies, including intrinsic activity of atomic sites or the ensemble, mesoscale bubble management, and macroscale transport phenomena, are strongly encouraged to comprehensively analyze total electrode activity. Such integrated approaches can yield reliable conclusions to guide development of next-generation 3D printed electrodes for high-rate water electrolysis.

Data availability

Not applicable.

Acknowledgements

T. Y. K. appreciates the funding support from the National Natural Science Foundation of China (No. 52301208), the Natural Science Foundation of Shandong Province (Nos. 2023HWYQ-019 and ZR2023QE142), Taishan Scholar Foundation of Shandong Province (No. tsqn202312074), and Basic Research Program of Jiangsu (No. BK20230259). The authors also thank the support from the Interdisciplinary Cultivation Program at Shandong University, Weihai.

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

H. X. W.: Writing – original draft. X. Y. S.: Writing – review & editing, supervision. G. M. W.: Writing – review & editing, supervision. T. Y. K.: Writing – review & editing, conceptualization, supervision, funding acquisition. All the authors have approved the final manuscript.

Use of AI statement

None.

References

- [1] Tüysüz, H. Alkaline water electrolysis for green hydrogen production. *Acc. Chem. Res.* **2024**, *57*, 558–567.
- [2] Lu, Q. C.; Yan, X. P.; Guo, W. Q.; Li, G. S.; Wang, J. Y.; Jiang, N.; Wang, X. L.; Ba, T. E.; Liu, P.; Zhou, J. N. et al. Research progress on alkaline anion exchange membranes (AEMs) for the application of hydrogen production by water electrolysis. *Nano Res.* **2025**, *18*, 94907252.
- [3] Qiu, J. X.; Yao, J. Y.; Feng, Z.; Huang, B. Y.; Luo, Z. Z.; Wang, L. L. Enhancing water electrolysis performance by bubble behavior management. *Small Methods* **2025**, *9*, 2402105.
- [4] Wang, H. P.; Xu, Z. X.; Lin, W.; Yang, X.; Gu, X. R.; Zhu, W.; Zhuang, Z. B. Improving the water electrolysis performance by manipulating the generated nano/micro-bubbles using surfactants. *Nano Res.* **2023**, *16*, 420–426.
- [5] Xu, N.; Qiu, B. B.; Rui, Z. C.; Ji, T. X.; Liu, Z. L.; Chu, H. Q. Effect of heat and bubble mass transfer on the efficiency of alkaline

- electrolysis hydrogen production. *Nano Res.* **2024**, *17*, 9345–9370.
- [6] Kou, T. Y.; Wang, S. W.; Li, Y. Perspective on high-rate alkaline water splitting. *ACS Mater. Lett.* **2021**, *3*, 224–234.
 - [7] Wang, K. L.; Pei, P. C.; Ma, Z.; Chen, H. C.; Xu, H. C.; Chen, D. F.; Xing, H. Q. Growth of oxygen bubbles during recharge process in zinc–air battery. *J. Power Sources* **2015**, *296*, 40–45.
 - [8] Phillips, R.; Dunnill, C. W. Zero gap alkaline electrolysis cell design for renewable energy storage as hydrogen gas. *RSC Adv.* **2016**, *6*, 100643–100651.
 - [9] Kang, Y.; Lee, S.; Han, S.; Jeon, D.; Bae, M.; Choi, Y.; Lee, D. W.; Ryu, J. Versatile, stable, and scalable gel-like aerophobic surface system (GLASS) for hydrogen production. *Adv. Funct. Mater.* **2024**, *34*, 2308827.
 - [10] Kou, T. Y.; Wang, S. W.; Shi, R. P.; Zhang, T.; Chiovoloni, S.; Lu, J. Q.; Chen, W.; Worsley, M. A.; Wood, B. C.; Baker, S. E. et al. Periodic porous 3D electrodes mitigate gas bubble traffic during alkaline water electrolysis at high current densities. *Adv. Energy Mater.* **2020**, *10*, 2002955.
 - [11] Ju, Y. J.; Zhang, J. W.; Cai, Q. Y.; Zhang, Z. Z.; Zhao, Y.; Cui, J. G.; Hou, R. E.; Wei, Y.; Liang, Z. Q.; Chen, F. J. Rotary-angle 3D printing multilayer membrane dead-end filtration for rapid and highly efficient water treatment. *Chem. Eng. J.* **2023**, *453*, 139969.
 - [12] Huang, B. R.; Wang, X. C.; Li, W. Z.; Tian, W. G.; Luo, L.; Sun, X. M.; Wang, G. W.; Zhuang, L.; Xiao, L. Accelerating gas escape in anion exchange membrane water electrolysis by gas diffusion layers with hierarchical grid gradients. *Angew. Chem., Int. Ed.* **2023**, *62*, e202304230.
 - [13] Fu, G. W.; Sun, X.; Zheng, Z. C.; Wang, Y. X.; Qiu, J. W.; Wu, Z. Z.; Chen, G.; Xu, X. Stereolithography of metallic electrode with Janus porosity toward controllable bubble behavior and ultra-stable water electrolysis. *Small Struct.* **2023**, *4*, 2300176.
 - [14] Ren, Q.; Feng, L. S.; Tran, C.; Eisenberg, S.; Xue, X. Z.; Pinongcos, A.; Duoss, E. B.; Zhu, C.; Li, Y. Interpenetrating 3D electrodes for high-rate alkaline water splitting. *ACS Mater. Lett.* **2024**, *6*, 3705–3712.
 - [15] Ren, Q.; Feng, L. S.; Ye, C. W.; Xue, X. Z.; Lin, D.; Eisenberg, S.; Kou, T. Y.; Duoss, E. B.; Zhu, C.; Li, Y. Nanocone-modified surface facilitates gas bubble detachment for high-rate alkaline water splitting. *Adv. Energy Mater.* **2023**, *13*, 2302073.
 - [16] Mojabi, S.; Afsahi, N.; Naseri, N. Additive manufacturing: New paradigm for developing water splitting systems. *Int. J. Hydrogen Energy* **2024**, *49*, 116–142.
 - [17] Scheideler, W. J.; Im, J. Recent advances in 3D printed electrodes-bridging the Nano to mesoscale. *Adv. Sci.* **2025**, *12*, 2411951.
 - [18] Khoo, V.; Ng, S. F.; Haw, C. Y.; Ong, W. J. Additive manufacturing: A paradigm shift in revolutionizing catalysis with 3D printed photocatalysts and electrocatalysts toward environmental sustainability. *Small* **2024**, *20*, 2401278.
 - [19] Zhou, S. X.; Ding, J. Utilize natural forces in water treatment through 3D-printed structures: From purification to clean energy. *Adv. Mater.* **2025**, *37*, e09185.
 - [20] Xun, Y. R.; Zhang, K. X.; Jonhson, W.; Ding, J. A minireview on 3D printing for electrochemical water splitting electrodes and cells. *APL Mater.* **2023**, *11*, 061119.
 - [21] Khan, S. A.; Koç, M. Advancing electrolyzer design through additive manufacturing: A review on 3D printing in hydrogen electrolysis. *Int. J. Hydrogen Energy* **2025**, *174*, 151240.
 - [22] Lee, C. Y.; Taylor, A. C.; Nattestad, A.; Beirne, S.; Wallace, G. G. 3D printing for electrocatalytic applications. *Joule* **2019**, *3*, 1835–1849.
 - [23] van der Linde, P.; Peñas-López, P.; Moreno Soto, Á.; van der Meer, D.; Lohse, D.; Gardeniers, H.; Fernández Rivas, D. Gas bubble evolution on microstructured silicon substrates. *Energy Environ. Sci.* **2018**, *11*, 3452–3462.
 - [24] Kalikmanov, V. I. Classical nucleation theory. In *Nucleation Theory*. Kalikmanov, V. I., Ed.; Springer: Dordrecht, 2013; pp 17–41.
 - [25] Brandon, N. P.; Kelsall, G. H. Growth kinetics of bubbles electrogenerated at microelectrodes. *J. Appl. Electrochem.* **1985**, *15*, 475–484.
 - [26] Zhao, X.; Ren, H.; Luo, L. Gas bubbles in electrochemical gas evolution reactions. *Langmuir* **2019**, *35*, 5392–5408.
 - [27] Li, J. F.; Xu, Q.; Luo, X. Y.; Nie, T. F.; Wang, M. S.; She, Y. L.; Guo, L. J. Size effects on bubble dynamics during photoelectrochemical water splitting. *ACS Nano* **2025**, *19*, 8200–8211.
 - [28] Oguz, H. N.; Prosperetti, A. Dynamics of bubble growth and detachment from a needle. *J. Fluid Mech.* **1993**, *257*, 111–145.
 - [29] Xu, W. W.; Lu, Z. Y.; Wan, P. B.; Kuang, Y.; Sun, X. M. High-performance water electrolysis system with double nanostructured superaerophobic electrodes. *Small* **2016**, *12*, 2492–2498.
 - [30] Li, M. X.; Xie, P. P.; Yu, L. F.; Luo, L.; Sun, X. M. Bubble engineering on micro-/nanostructured electrodes for water splitting. *ACS Nano* **2023**, *17*, 23299–23316.
 - [31] Yan, Q.; Chen, B.; Kang, N.; Lin, X.; Lv, S.; Kondoh, K.; Li, S.; Li, J. S. Comparison study on microstructure and mechanical properties of Ti–6Al–4V alloys fabricated by powder-based selective-laser-melting and sintering methods. *Mater. Charact.* **2020**, *164*, 110358.
 - [32] Sing, S. L.; Yeong, W. Y.; Wiria, F. E.; Tay, B. Y.; Zhao, Z. Q.; Zhao, L.; Tian, Z. L.; Yang, S. F. Direct selective laser sintering and melting of ceramics: A review. *Rapid Prototyp. J.* **2017**, *23*, 611–623.
 - [33] Al Rashid, A.; Ahmed, W.; Khalid, M. Y.; Koç, M. Vat photopolymerization of polymers and polymer composites: Processes and applications. *Addit. Manuf.* **2021**, *47*, 102279.
 - [34] Ge, Q.; Li, Z. Q.; Wang, Z. L.; Kowsari, K.; Zhang, W.; He, X. N.; Zhou, J. L.; Fang, N. X. Projection micro stereolithography based 3D printing and its applications. *Int. J. Extrem. Manuf.* **2020**, *2*, 022004.
 - [35] Melchels, F. P. W.; Feijen, J.; Grijpma, D. W. A review on stereolithography and its applications in biomedical engineering. *Biomaterials* **2010**, *31*, 6121–6130.
 - [36] Xu, X.; Tan, Y. H.; Ding, J.; Guan, C. 3D printing of next-generation electrochemical energy storage devices: From multiscale to multimaterial. *Energy Environ. Mater.* **2022**, *5*, 427–438.
 - [37] Goodarzi Hosseinabadi, H.; Dogan, E.; Miri, A. K.; Ionov, L. Digital light processing bioprinting advances for microtissue models. *ACS Biomater. Sci. Eng.* **2022**, *8*, 1381–1395.
 - [38] Huddy, J. E.; Rahman, M. S.; Hamlin, A. B.; Ye, Y. X.; Scheideler, W. J. Transforming 3D-printed mesostructures into multimodal sensors with nanoscale conductive metal oxides. *Cell Rep. Phys. Sci.* **2022**, *3*, 100786.
 - [39] Skylar-Scott, M. A.; Mueller, J.; Visser, C. W.; Lewis, J. A. Voxellated soft matter via multimaterial multinozzle 3D printing. *Nature* **2019**, *575*, 330–335.
 - [40] Fu, J.; Wang, D.; Li, Y.; Liu, X. Z.; Zhang, R.; Liu, Z. Y.; Liu, P. D.; Zhang, L. J.; Li, X. F.; Wen, G. W. 3D printed silicon-based micro-lattices with ultrahigh areal/gravimetric capacities and robust structural stability for lithium-ion batteries. *Nano Res.* **2024**, *17*, 2693–2703.
 - [41] Ho, J. Y.; Rabbi, K. F.; Khodakarami, S.; Sett, S.; Wong, T. N.; Leong, K. C.; King, W. P.; Miljkovic, N. Ultrascable surface structuring strategy of metal additively manufactured materials for enhanced condensation. *Adv. Sci.* **2022**, *9*, 2104454.
 - [42] Shahzadi, L.; Maya, F.; Breadmore, M. C.; Thickett, S. C. Functional materials for DLP-SLA 3D printing using thiol-acrylate chemistry: Resin design and postprint applications. *ACS Appl. Polym. Mater.* **2022**, *4*, 3896–3907.
 - [43] Zhu, G. D.; von Coelln, N.; Hou, Y.; Vazquez-Martel, C.; Spiegel, C. A.; Tegeer, P.; Blasco, E. Digital light 3D printing of double thermoplastics with customizable mechanical properties and versatile reprocessability. *Adv. Mater.* **2024**, *36*, 2401561.
 - [44] Wang, Y. J.; Li, X.; Fan, S. F.; Feng, X. B.; Cao, K.; Ge, Q.; Gao, L. B.; Lu, Y. Three-dimensional stretchable microelectronics by projection microstereolithography (PuSL). *ACS Appl. Mater. Interfaces* **2021**, *13*, 8901–8908.
 - [45] Xu, C.; Xu, Y.; Chen, H.; Han, Q.; Wu, W. Z.; Zhang, L.; Liu, Q. P.; Wang, J. C.; Ren, L. Q. Novel-ink-based direct ink writing of

- Ti6Al4V scaffolds with sub-300 μm structural pores for superior cell proliferation and differentiation. *Adv. Healthcare Mater.* **2024**, *13*, 2302396.
- [46] Chen, J. X.; Fu, G. W.; Tian, Y.; Li, X. C.; Luo, M. Q.; Wei, X. Y.; Zhang, T.; Gao, T.; Chen, C.; Chaemchuen, S. et al. Three-dimensional-printed Ni-based scaffold design accelerates bubble escape for Ampere-level alkaline hydrogen evolution reaction. *Interdiscip. Mater.* **2024**, *3*, 595–606.
- [47] Feng, Z. J.; Wang, H.; Jiang, N. N.; Liu, X. W.; Jin, H. H.; Cheng, H. Y.; Guan, L. H. Optimized bubble dynamics of 3D-printed electrodes for enhanced water splitting. *ACS Appl. Mater. Interfaces* **2025**, *17*, 15446–15455.
- [48] Wu, Q. R.; Wang, H.; Lang, Y. W.; Yao, Y. N.; Liu, X. W.; Wu, J.; Zhang, J. W.; Yang, X. X.; Guan, L. H. 3D microporous structure with tunable surface roughness enables fast bubble dynamics for efficient water splitting. *Small Methods* **2025**, *9*, e01245.
- [49] Schoen, A. H. Infinite periodic minimal surfaces without self-intersections. NASA, 1970.
- [50] Rocha, F.; Delmelle, R.; Georgiadis, C.; Proost, J. Electrochemical performance enhancement of 3D printed electrodes tailored for enhanced gas evacuation during alkaline water electrolysis. *Adv. Energy Mater.* **2023**, *13*, 2203087.
- [51] Xun, Y. R.; Jin, H. M.; Li, Y. M.; Zhou, S. X.; Zhang, K. X.; Xu, X.; Jonhson, W.; Chang, S.; Tan, T. L.; Ding, J. 3D-printed monolith metallic Ni–Mo electrodes for ultrahigh current hydrogen evolution. *Energy Environ. Mater.* **2024**, *7*, e12714.
- [52] Liao, N.; Zhao, J.; Luo, J. S. 3D-printed metal electrodes with enhanced bubble removal for efficient water electrolysis. *Nano Lett.* **2025**, *25*, 9551–9559.
- [53] Zeng, T. B.; Guo, B. B.; Xu, Z. Y.; Mo, F. N.; Chen, X. T.; Wang, L. P.; Ding, Y. H.; Bai, J. M. Manageable bubble release through 3D printed microcapillary for highly efficient overall water splitting. *Adv. Sci.* **2023**, *10*, 2207495.
- [54] Yu, L. F.; Yang, Y. Z.; Xie, P. P.; Xu, Q. Z.; Kumar, A.; Luo, L.; Li, H.; Xu, H. J.; Duan, H. H.; Sun, X. M. Unidirectional bubble transportation on slippery micro-cone array electrodes enables spontaneous 99.99% gas separation in membrane-less water electrolysis. *EES Catal.* **2025**, *3*, 152–160.
- [55] Das, R.; Benjamim, R.; Kotal, M.; Machado, L.; Galvao, D. S.; Tiwary, C. S. Hydrogen evolution reactions using 3D printed composites of copper with graphene and hexagonal boron nitride. *Chem. Commun.* **2025**, *61*, 9039–9042.
- [56] Guo, B. B.; Kang, J. H.; Zeng, T. B.; Qu, H. Q.; Yu, S. X.; Deng, H.; Bai, J. M. 3D printing of multiscale Ti64-based lattice electrocatalysts for robust oxygen evolution reaction. *Adv. Sci.* **2022**, *9*, 2201751.
- [57] Guo, B. B.; Lin, J.; Mo, F. N.; Ding, Y. H.; Zeng, T. B.; Liang, H. W.; Wang, L. P.; Chen, X. T.; Mo, J. W.; Li, D. S. et al. Robust and corrosion-resistant overall water splitting electrode enabled by additive manufacturing. *Small* **2024**, *20*, 2312216.
- [58] Selamet, O. F.; Pasaogullari, U.; Spornjak, D.; Hussey, D. S.; Jacobson, D. L.; Mat, M. *In-situ* two-phase flow investigation of proton exchange membrane (PEM) electrolyzer by simultaneous optical and neutron imaging. *Meet. Abstr.* **2011**, *MA2011-02*, 978.
- [59] Lee, J. K.; Lee, C.; Fahy, K. F.; Zhao, B. Z.; LaManna, J. M.; Baltic, E.; Jacobson, D. L.; Hussey, D. S.; Bazylak, A. Critical current density as a performance indicator for gas-evolving electrochemical devices. *Cell Rep. Phys. Sci.* **2020**, *1*, 100147.
- [60] Altaf, H.; Milicic, T.; Vidakovic-Koch, T.; Tsotsas, E.; Tengattini, A.; Kardjilov, N.; Arlt, T.; Manke, I.; Vorhauer-Huget, N. Neutron imaging experiments to study mass transport in commercial titanium felt porous transport layers. *J. Electrochem. Soc.* **2023**, *170*, 064507.
- [61] Wei, X.; Li, J. Q.; Liang, W. H.; Ma, C.; Zhou, T. F.; Zhang, Q.; Wang, L. L.; Yu, K. H.; Wei, W. Quantifying bubble dynamics via fiber optic sensor for *in-situ* electrocatalytic evaluation. *Nano Res.* **2025**, *18*, 94907699.
- [62] Wei, X.; Wu, Y.; Zhou, T. F.; Li, J. Q.; Liang, W. H.; Ma, C.; Zhang, Q.; Hu, E. T.; Zheng, J. J.; Sun, B. et al. Breaking the black box of water electrolyzers: *In-situ* fiber-optic bubble monitoring guided system-level optimization. *Nano Energy* **2025**, *144*, 111388.



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Nano Research, 2026, 19, 94908521