

Chiral inorganic films: Structural fabrication and functional application analysis

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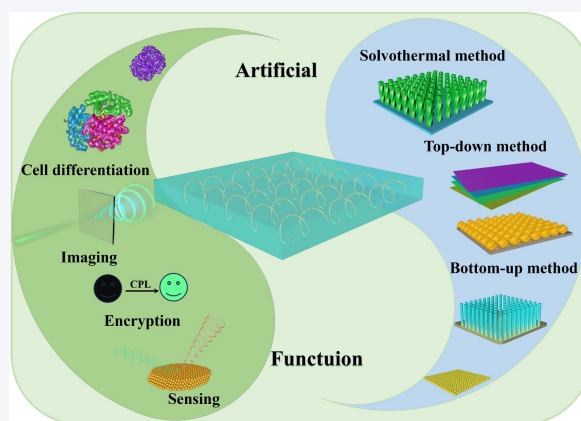
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ABSTRACT: Chirality is a fundamental and ubiquitous property in nature. As two-dimensional functional materials with chiral structures and optical activity, chiral inorganic thin films show broad prospects in biosensing, optoelectronic devices, spintronics, and pharmaceutical separation, due to their unique properties (chiral recognition, symmetric chiral catalysis, circularly polarized light response, and spin filtering). This review systematically summarizes the fabrication methods of chiral inorganic thin films, focusing on the mechanisms, characteristics, and research progress of mainstream technologies (bottom-up self-assembly, solvothermal method, top-down method) for chiral inorganic thin film systems. It outlines their core properties and application status in optics, catalysis, sensing, and spintronics, with specific examples illustrating application value. Finally, it discusses key issues in current research and prospects future development trends. Covering chiral inorganic metal oxides, noble metals, and other systems, this review highlights the advantages and research potential of different chiral thin films, providing comprehensive references for their subsequent design, preparation, and functional expansion.

KEYWORDS: chiral inorganic films, chiroptical response, structural analysis, structure and performance



1 Introduction

Chirality, a fundamental geometric property defined as the non-superimposability of an object and its mirror image, is widely prevalent in nature—from biological macromolecules (e.g., amino acids, DNA) to artificial materials [1–3]. In recent decades, chiral materials have garnered tremendous attention for their unique chiroptical, spin-dependent, and enantioselective properties, spawning promising applications in optoelectronics, biomedicine, catalysis, information encryption, and spintronics [4–15]. Among them, chiral organic and polymeric thin films were the first to be developed, whereas their inherent limitations—poor thermal stability, poor chemical resistance, and weak mechanical robustness severely restrict practical application in harsh environments (e.g., high temperature, complex physiological conditions, and strong light

irradiation) [16–19]. To address these bottlenecks, chiral inorganic thin films have emerged as a new generation of chiral functional materials, integrating inorganic materials' intrinsic advantages (high stability, excellent mechanical properties, abundant raw materials) with unique chiral characteristics (chiral recognition, circularly polarized luminescence, spin selectivity) [5, 14, 20]. Unlike organic counterparts relying on chiral molecular units, they achieve chirality via intrinsic crystal asymmetry, external induction (ligands, topology, external fields), or composite modification, forming a diverse category including metal oxides, metal halides, chalcogenides, noble metals, carbon-based materials, and their composites [21–26].

In recent years, with in-depth research on the chiral-induced spin selectivity (CISS) effect, circular dichroism (CD), and circularly polarized luminescence (CPL) properties, chiral inorganic thin films have exhibited unprecedented application potential in multiple frontier fields [26]. In optoelectronics, their high CPL quantum efficiency and wide spectral tunability make them core candidates for next-generation 3D displays, circularly polarized light detectors, and quantum light sources [27]. In biomedicine, their good biocompatibility, CISS-mediated selective antibacterial activity, cell behavior regulation, and low inflammatory properties render them

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ideal for neural interfaces, tissue engineering, chiral biosensing, and targeted therapy [28]. In spintronics, the CISS effect enables spin polarization without external magnetic fields, offering a new pathway for low-power spin storage and logic devices [29]. They also hold great promise in chiral catalysis, enantiomer separation, high-end anticounterfeiting, and environmental governance [30–33].

Despite their rapid development, chiral inorganic thin films still face several critical challenges: the mechanisms of chiral transfer and spin-chiral coupling in inorganic systems remain incompletely elucidated; the chiroptical activity (e.g., CPL asymmetry factor, spin polarization efficiency) of most materials still fails to meet practical application requirements; scalable fabrication of high uniformity chiral films and their integration with existing devices remain challenging; the development of environmentally friendly, and biocompatible chiral inorganic systems is urgent [34]. Additionally, a systematic summary of the classification, preparation, properties, and applications of chiral inorganic thin films is lacking, hindering in-depth understanding and further advancement of this field.

In this review, we comprehensively summarize the latest research progress of chiral inorganic thin films (Fig. 1). This graphic is structurally divided into three interrelated modules to deliver comprehensive introductory guidance for readers. The left timeline systematically sorts out the milestone evolution trajectory of chiral inorganic thin films, ranging from early discrete chiral nanoparticles, ligand-functionalized noble metal thin films, oxide chiral films with verified chirality transfer mechanisms, to state-of-the-art multimetallic helical superstructure thin films. The central section summarizes the core intrinsic characteristics of such films, covering asymmetric geometric lattice configuration, characteristic chiroptical circular dichroism responses, interfacial organic–inorganic chirality transfer pathways, and unique spin-selective electronic behaviors. The right panel presents the current research frontiers, including prevailing material categories, representative application directions (electrochemical chiral biomolecule

detection, circularly polarized optoelectronic devices, asymmetric electrocatalysis, spin photonic components). Guided by logical connecting arrows, the three modules form a complete research context, enabling readers to rapidly grasp the development logic, fundamental mechanisms and cutting-edge progress of this field.

On this basis, this review first classify chiral inorganic thin films based on chiral origin, chemical composition, microstructural dimension, and functional applications. Then, we systematically introduce the preparation methods of different types of chiral inorganic thin films and the regulation strategies for their chiral properties. Furthermore, we focus on their core properties (chiroptical properties, CISS effect, biocompatibility) and their intrinsic mechanisms. Finally, we discuss their practical applications in optoelectronic domains, biomedicine, spintronics, catalysis, and other fields, analyze prevailing technical bottlenecks, and prospect future development trends. This review aims to provide a comprehensive reference for researchers in related fields and promote the rapid development and industrialization of chiral inorganic thin films.

2 Classification

Chiral inorganic thin films exhibit diverse structures, chemical components and chiral characteristics, which lay a foundation for their multifunctional applications in various fields. To systematically understand the research progress and application potential of chiral inorganic thin films, a scientific and reasonable classification system based on preparation methods is essential. Among numerous preparation strategies, bottom-up self-assembly method, solvothermal method and top-down method are the three most widely used and representative approaches, which dominate the microstructures, chiral properties and application prospects of the films. Each classification category based on these methods has distinct preparation principles, characteristics and typical material cases, which are elaborated in detail as follows.

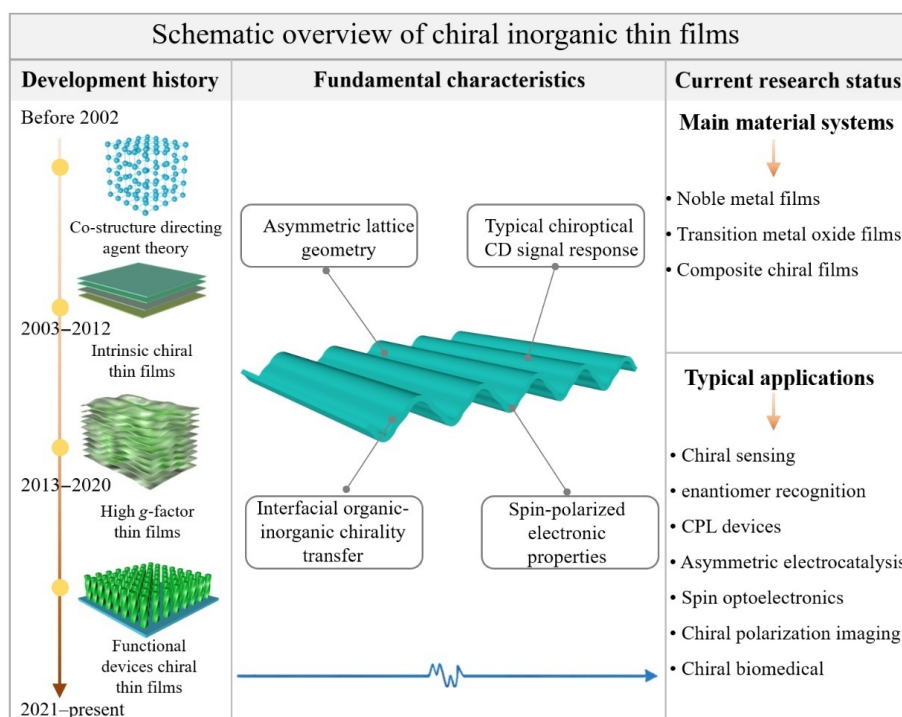


Figure 1 Schematic of the development history, fundamental characteristics, and current research status of chiral inorganic thin films.

2.1 Bottom-up self-assembly method

The bottom-up self-assembly method refers to the spontaneous assembly of low-dimensional inorganic nanounits into macroscopic chiral thin films through non-covalent interactions without external force intervention [21, 23, 35, 36]. This method is characterized by mild reaction conditions, simple operation, and the ability to accurately regulate the chiral handedness and microstructures of the films, which is widely used in the preparation of various chiral inorganic thin films with uniform chiral properties [37, 38]. The core principle of this method lies in the transfer and amplification of chiral information: chiral molecules or chiral nanounits act as “building blocks”, and their chiral characteristics are transferred to the entire film through ordered self-assembly, forming macroscopic chiral structures [7, 34, 39–42]. The Ki Tae Nam’s team integrates the bottom-up Self-assembly of inorganic nanomaterials with spatiotemporal modulation technology to construct chiral polarization films for high-security optical encryption (Figs. 2(a)–2(c)) [41]. First, ultrathin inorganic nanowires and quantum nanorods are selected as the low-dimensional building units, and

the uniform dispersion of the nanounits is realized by adjusting the precursor concentration and solvent ratio to ensure the uniformity of the self-assembly foundation. Then, during the 3D printing filament protruding process, the shear force generated by the extrusion of the filament is used as the external induction force to guide the directional alignment of the inorganic nanounits—this is the key to realizing ordered self-assembly, which solves the problem of random stacking of nanounits in traditional self-assembly methods. The shear force parameters (shear rate, extrusion pressure) are precisely regulated to control the alignment degree of nanounits, so that the assembled thin film forms a uniform chiral plasmonic structure. Finally, the self-assembled chiral film is positioned and patterned by 3D printing technology, realizing the integration of self-assembly and patterning. The core advantage of this method is that it combines the spontaneity of bottom-up Self-assembly with the precise controllability of 3D printing, and the shear-force-induced alignment can effectively improve the polarization degree of the film ($\text{DOP} > 0.8$). The key technical point lies in the matching between shear force parameters and nanounit

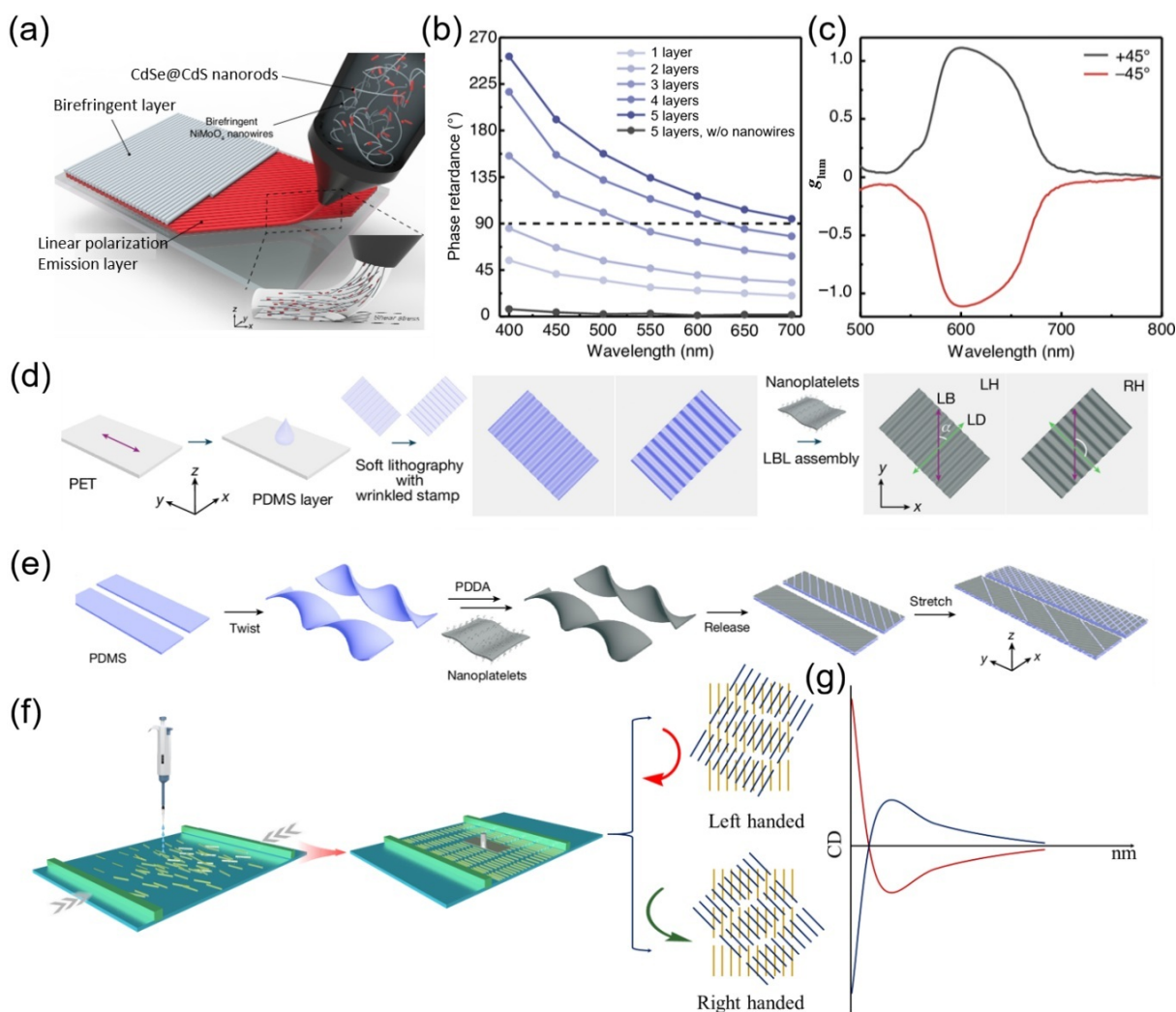


Figure 2 (a) Schematic of 3D printing for a single CPL pixel based on CdSe@CdS NRs and NiMoO₄·xH₂O NWs; (b) layer-number-dependent phase retardation of the printed NW film; (c) g_{nm} of the printed CPL films. +45° means the phase retardation layer is oriented at +45° relative to the alignment direction of the luminescent layer. Reproduced with permission from Ref. [41], © Nature Publishing Group 2024. (d) Schematics of nanocomposites based on 2D nanomaterials via M1 and (e) schematics of M2. Reproduced with permission from Ref. [40], © Lu, J. et al. 2021, some rights reserved; exclusive licensee American Association for the Advancement of Science. (f) Schematic fabrication process of CdSe/CdS nanorod chiral films via Langmuir–Schaeffer technique; (g) simulate CD spectra. Reproduced with permission from Ref. [43], © Wiley-VCH GmbH 2021.

size, which directly determines the order of self-assembly and the final chiroptical properties of the film. This method expands the application of bottom-up self-assembly in the field of optical encryption by realizing the spatiotemporal regulation of chiral polarization. Additionally, the Nicholas A. Kotov's team adopted the layer-by-layer (LBL) bottom-up self-assembly method to realize the chiral assembly of achiral inorganic nanomaterials (Figs. 2(d) and 2(e)) [40]. Achiral 2D inorganic nanoplates (MXene, MoS₂, graphene oxide) with nanoscale disorder were selected as building units. The core of this methodology lies in LBL assembly-mediated layer-by-layer stacking of 2D nanoplates via inter-nanoplate non-covalent interactions. Precisely controlled assembly speed, temperature, and pH during the process induce diagonal texture structures (wrinkles, grooves) on the film surface these textures are pivotal for generating chiroptical responses, as they induce an angular offset between the film's linear birefringence (LB) and linear dispersion (LD) axes, thereby conferring macroscopic chirality to achiral nanounits. This LBL strategy features modular assembly, allowing combination of different 2D nanoplates to tune film chiral properties. Key technical requirements include surface modification of 2D nanoplates (to enhance interlayer interactions and stacking compactness) and precise regulation of assembly parameters (to control diagonal texture formation). This approach breaks the conventional notion that achiral inorganic nanomaterials cannot yield strong chiroptical responses; its LBL assembly also ensures excellent film thermal stability (stable at 250 °C), providing a novel technical route for bottom-up fabrication of chiral inorganic thin films suitable for extreme environments.

In addition with the LBL assembly strategy, the Ziyong Tang and Hua Kuang's team developed another representative Bottom-up approach for chirality induction from achiral inorganic nanomaterials, namely a layer tunable ordered self-assembly method based on the Langmuir-Schaeffer (LS) technique (Figs. 2(f) and 2(g)) [21, 43, 44]. Achiral CdSe/CdS semiconductor nanorods were self-assembled into compact chiral thin films via two critical LS steps: spreading nanorods at the water-air interface (with surface pressure adjusted for dense, ordered monolayers) and layer-by-layer vertical transfer to the substrate, with precise control over layer number and interlayer angle. Optimal chiral performance was achieved with 10 layers (5 right-handed + 5 left-handed) and a 45° interlayer angle. Based on the Reusch model, ordered nanorod stacking forms helical crystal plates, where linear birefringence generates strong circular birefringence and macroscopic chirality. Key technical parameters include interface surface pressure (ensuring monolayer order) and interlayer angle (tuning chiroptical activity). This method induces chirality from achiral nanorods, with the LS technique ensuring film uniformity and compactness, endowing it with ultra-strong CD activity (1431 mdeg) and intense CPL ($g = 0.0997$), providing critical technical references for high-performance chiral optoelectronic films.

To conclude the above representative bottom-up self-assembly strategies, distinct operational routes universally follow the intrinsic mechanism of bottom-up fabrication: low-dimensional inorganic nanounits serve as fundamental building blocks, which assemble into ordered architectures through noncovalent interactions, and further realize chiral induction or signal amplification to construct macroscopic chiral thin films. Shear-force assisted assembly integrated with 3D printing enables precise nanoscale alignment and patterned fabrication, catering to chiral films for high-security optical encryption. LBL self-assembly achieves modular stacking of

achiral nanomaterials and surface texture engineering, offering a feasible route for chiral films deployed under extreme conditions. In contrast, LS-based layer-regulated assembly relies on accurate control of stacking layers and interlayer angles, which is applicable to high-performance CPL-active chiral optoelectronic films.

These approaches demonstrate the excellent flexibility and diversification of bottom-up technology. They share prominent merits including mild synthetic conditions, facile procedures, and controllable chiral configuration via rational assembly modulation. Nevertheless, they are still restricted by inferior mechanical robustness compared with top-down counterparts, and their environmental durability under complex service conditions remains to be further improved. Overall, the above research advances the methodological system of bottom-up assembled chiral inorganic thin films, and provides instructive guidelines for the targeted design and customized preparation of multifunctional chiral inorganic film materials.

In addition to achiral building blocks, chiral nanomaterials also serve as important building blocks for constructing functional architectures. The Ki Tae Nam's team used the chiral Au NPs as building blocks to prepare chiral films (Fig. 3(a)–3(d)) [36]. Taking advantage of the surface tension, capillary force, and solvent evaporation-induced effect at the water-air interface, the nanoparticles spontaneously arrange to form a long-range ordered, dense monolayer two-dimensional (2D) film. To meet the requirements of collective CD, the assembled particles present a hexagonal close-packed structure, generating a coupled plasmonic chiral collective effect. Key technical factors include rational screening of chiral ligands for efficient chiral information transfer and precise assembly modulation to acquire ordered arrays with prominent collective chiral responses. This strategy highlights the unique superiority of bottom-up assembly in chiral signal amplification and broadens the application scope of chiral inorganic films in high-sensitivity chiral sensing. Furthermore, Nam's group further developed a template-assisted transfer assembly strategy to realize the precise arrangement of chiral nanostructures and the integration of surface plasmon resonance (SPR) sensing function (Figs. 3(e) to 3(h)) [37]. This route inherits the mild conditions of bottom-up assembly and resolves the poor substrate compatibility of chiral nanostructures. Pre-synthesized helical chiral nanoparticles were confined within the nanopore arrays of prefabricated PDMS templates with fixed square intervals, achieving preliminary ordered localization. The gold film substrate was chemically modified via mixed silane functionalization to form robust amine-metal interfacial interactions. Through template compression and interfacial bonding, helical nanoparticles were uniformly transferred onto the functionalized substrate, constructing continuous chiral films with helical grating architectures. Combining spontaneous self-assembly with template positioning, this method well preserves the intrinsic chiral morphology of nano units while guaranteeing macroscopic film homogeneity. Precise template patterning and substrate functionalization are essential to optimize interfacial adhesion and structural matching. The integrated design of chiral configuration and SPR response endows the as-prepared films with dual advantages of strong chiroptical activity and high sensing performance, offering a novel route for the fabrication of chiral thin-film sensors. Moreover, the Liz-Marzán's team proposed a groove-confined assembly strategy to synchronously modulate intrinsic and extrinsic chiroptical responses (Figs. 3(i)–3(n)) [45]. Overcoming

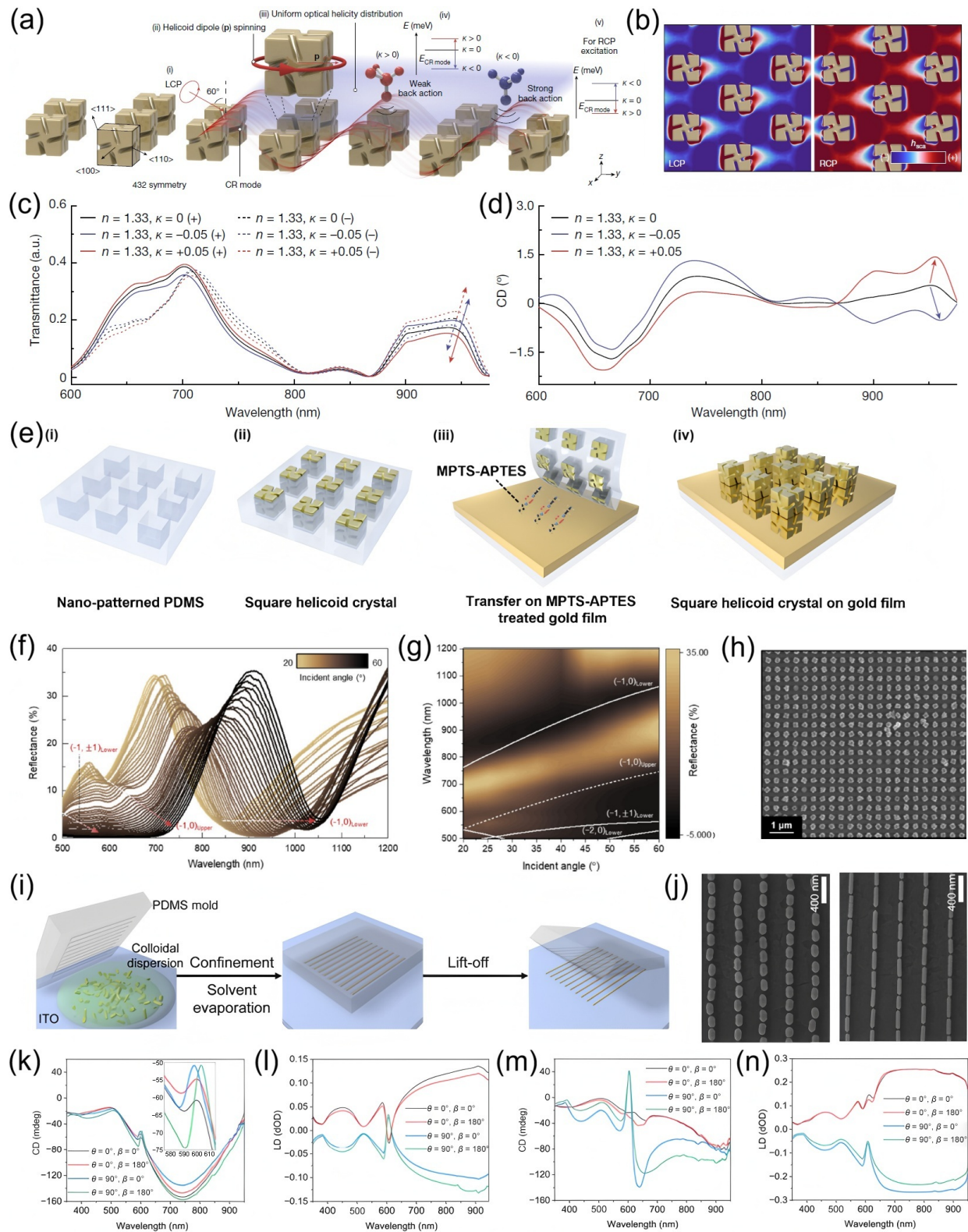


Figure 3 (a) Schematic of enantioselective sensing of a 2D helicoid crystal; (b) spatial distributions of HSCA at 965 nm (CR) under 60° oblique incidence of LCP (left) and RCP (right) light; (c) transmittance spectra of 2D helicoid crystals immersed in chiral molecular media with $\kappa = 0$ (racemic), $\kappa < 0$ (D-molecules), and $\kappa > 0$ (L-molecules) under LCP (+, solid line) and RCP (–, dashed line) illumination. LCP transmittance exhibits asymmetric shift for opposite chiral molecules; (d) CD spectra ($T_- - T_+$) for media with $\kappa = 0$, $\kappa < 0$ and $\kappa > 0$. The asymmetric transmittance shift induces distinct variations in CD peaks. Reproduced with permission from Ref. [36], © Kim, R. M. et al., under exclusive licence to Springer Nature Limited 2022. (e) Schematic fabrication of square helicoid crystal on Au film; (f) color map of angle-resolved reflectance spectra; (g) SEM image of chiral Au film. Reproduced with permission from Ref. [37], © American Chemical Society 2024. (i) Schematics of NP array fabrication via template-assisted self-assembly; (j)–(n) representative SEM image, CD and LD spectra measured at different orientations. Reproduced with permission from Ref. [45], © Chow, T. H. et al. 2026. Published by American Chemical Society.

the difficulty in distinguishing and regulating multiple CD components in traditional assembly systems. Highly anisotropic chiral Au nanorods with surface chiral wrinkles and intrinsic chirality were assembled within linear-groove PDMS templates. Controlled by solvent evaporation dynamics, chiral nanorods docked end-to-end to form periodic one-dimensional linear arrays with tunable spacing. The synergistic regulation of solvent volatilization rate, groove dimension and nanorod concentration ensured highly ordered alignment. The resultant arrays simultaneously exhibited dual CD signals: intrinsic CD originating from the surface chiral topography of individual nanorods, and extrinsic CD derived from the periodic collective arrangement of the whole array. Precise control of template microstructure and array periodicity enables flexible manipulation of dual chiral signals. The obtained plasmonic films possess a high dissymmetry factor (g -factor up to ± 0.1) and excellent quality factor ($Q \approx 63$), providing reliable technical guidance for high-performance chiral plasmonic materials toward photonics and chiral sensing.

Taken together, these chiral building blocks-based bottom-up strategies follow a unified core mechanism: low-dimensional chiral nano units form ordered configurations via noncovalent interactions and template confinement, accompanied by effective chiral information transfer and amplification to construct macroscopic chiral films. Supramolecular coordination-driven assembly focuses on chiral signal enhancement for trace enantiomer detection; template-assisted transfer assembly realizes device-compatible chiral integration for SPR sensing; and groove-confined linear assembly achieves dual regulation of intrinsic and extrinsic CD responses. Collectively, these approaches demonstrate the great flexibility and functional expandability of bottom-up technology. Consistent with foregoing characteristics, they feature mild conditions and adjustable chiral performance, while the inherent limitation of insufficient mechanical strength and long-term environmental stability still requires further optimization. These advances substantially supplement the technical system of bottom-up-assembled chiral inorganic thin films, greatly promote their development in chiral sensing, and provide rational design principles for high-sensitivity, controllable chiral functional film materials.

2.2 Solvothermal method

Chiral solvothermal synthesis is a typical wet-chemical route, in which inorganic precursors react in a sealed autoclave with aqueous or organic media under controlled temperature and pressure. This method combines the advantages of solution reaction and high-temperature high-pressure reaction, which can effectively regulate the crystal growth and chiral structure of inorganic materials, and is widely used in the preparation of chiral inorganic thin films with high crystallinity and stable chiral properties (Fig. 4(a)) [26]. In the process of preparing chiral inorganic thin films by solvothermal method, chiral induction agents (e.g., chiral amino acids, chiral small organic molecules) are usually added to the reaction system to guide the asymmetric growth of inorganic crystals, thereby introducing chirality into the films. The reaction temperature, pressure, reaction duration and the type of chiral induction agent are the key factors affecting the chiral characteristics and microstructures of the films. By adjusting these parameters, chiral thin films with different chiral handedness, crystal phases and microstructures can be obtained [6]. The Che Shunai's team has systematically advanced this field (Figs. 4(b)–4(m)). A series of high-

quality chiral inorganic thin films have been successfully synthesized via chiral solvothermal strategies, including chiral Ag film [46], chiral Pd film [47], chiral Au film [48], chiral Fe_3O_4 film [49], chiral $\text{Ni-Fe}_3\text{O}_4$ film [50], chiral BiOBr film [51], chiral In_2O_3 film [52], etc., which have intrinsic chirality and good biocompatibility [53, 54].

The advantages of this method are high crystallinity of the prepared thin films, stable chiral properties, and good adhesion to the substrate; the disadvantage is that the reaction conditions are relatively harsh (needing high temperature and high pressure), the operation is complex, and it is not easy to large-scale industrial production. This method is suitable for the preparation of chiral thin films used in high-performance optoelectronic devices, catalysis and other fields that require high crystallinity.

2.3 Top-down method

The top-down method fabricates chiral inorganic thin films by physically or chemically processing bulk inorganic materials or achiral inorganic thin films to introduce chiral structures, featuring high precision, excellent controllability, and capability to prepare films with complex microstructures, thus being widely applied in device-integrated chiral thin films [55, 56]. Common top-down technologies include photolithography combined with reactive ion etching (RIE), laser direct writing, nanoimprint patterning, and glancing angle deposition (GLAD). Photolithography-RIE, the most widely used industrial technology, enables high-resolution chiral patterning (feature size down to $1\ \mu\text{m}$) for on-chip integration; GLAD prepares helical and twisted chiral nanostructured films by controlling substrate inclination and rotation during deposition; laser direct writing achieves high-precision direct fabrication of chiral structures on inorganic film surfaces. Typical products include: photolithography-RIE-prepared micron-scale chiral perovskite films (for optoelectronic on-chip integration), GLAD-fabricated helical Au/Ag nanoscale films (with strong localized surface plasmon resonance and chiroptical response), laser-written chiral carbon-based films (with precise chiral structure control), and chiral metal oxide films (etched via chiral templates, with stable structures and good mechanical properties) [57].

This method boasts high precision, controllability, and high mechanical strength of films, but suffers from high equipment investment, complex preparation processes, and potential damage to film chiral properties during processing. It is suitable for high-precision, high-mechanical-strength scenarios such as brain-computer interfaces and spintronic devices. The top-down method has been advanced by several research teams through innovative technical optimization, addressing traditional bottlenecks while enhancing performance and expanding application scenarios [58]. The Yan Jun Liu's team developed a one-step electron beam lithography (EBL) combined with metal evaporation and lift-off strategy to fabricate ultrathin suspended chiral bilayer metasurfaces (Figs. 5(a) and 5(b)) [59]. This methodology resolves the complex procedures and alignment errors of conventional top-down approaches, enabling one-step fabrication of suspended chiral bilayer structures with a mere $100\ \text{nm}$ thickness and a high optical chirality of $221\ \text{°}/\mu\text{m}$. The suspended design facilitates full contact between the meta surface and chiral molecule solutions, achieving zeptomole-level label-free chiral molecule discrimination fully embodying the top-down method's strengths in high-precision structure fabrication and high-sensitivity sensing. Complementarily, the Wending Zhang's team proposed a one-step EBL integrated

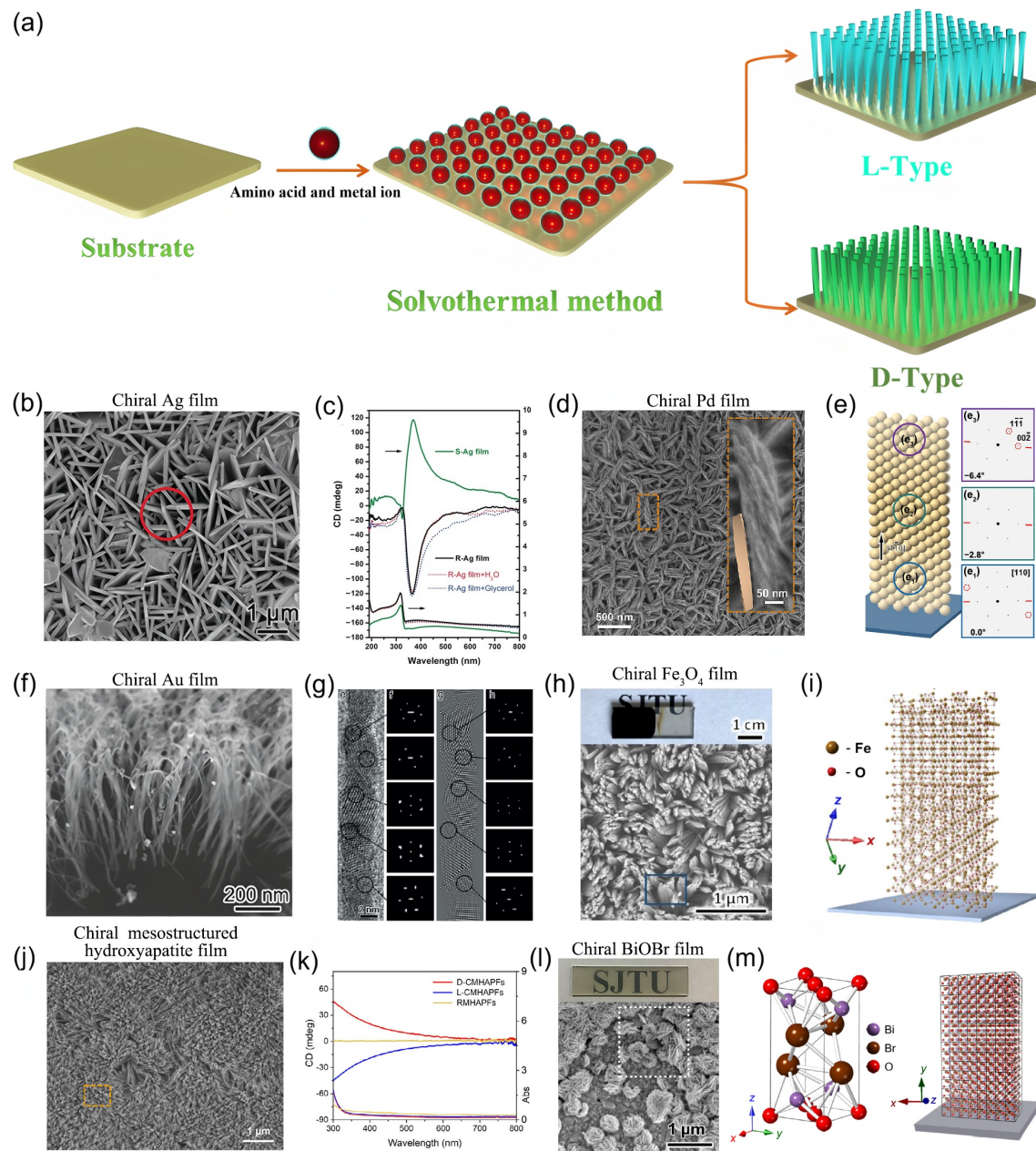


Figure 4 (a) Fabrication of chiral mesostructured metal oxide films; (b) SEM image of chiral Ag film; (c) CD spectra of Ag film. Reproduced with permission from Ref. [46], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2017. (d) SEM image of chiral Pd film and (e) structural model of L-CNPFs viewed along the [110] direction. Reproduced with permission from Ref. [47], © Elsevier B.V. 2025. (f) SEM image of chiral Au film and (g) HR-TEM images. Reproduced with permission from Ref. [48], © Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim 2020. (h) SEM image of chiral Fe_3O_4 film and (i) crystal structure and growth direction of Fe_3O_4 nanoflakes on the substrate. Reproduced with permission from Ref. [49], © Wiley-VCH GmbH 2021. (j) SEM image of chiral mesostructured hydroxyapatite film. Reproduced with permission from Ref. [25], © Wiley-VCH GmbH 2025. (k) CD spectra of mesostructured hydroxyapatite film. Reproduced with permission from Ref. [25], © Wiley-VCH GmbH 2025. (l) SEM image of chiral BiOBr film and (m) crystal structure and growth direction of BiOBr nanoflakes on the FTO substrate. Reproduced with permission from Ref. [51], © Wiley-VCH GmbH 2021.

with unidirectional thermal evaporation deposition to fabricate 3D intrinsic chiral metamaterials (Fig. 5(c)) [55]. Breaking the limitations of traditional top-down methods (reliance on complex multi-step lithography/GLAD and low optical asymmetry factors), this approach boasts excellent material universality (applicable to dielectrics, semiconductors, and metals) and achieves a record-high g -factor of 1.3 at 770 nm (visible region)-over an order of magnitude higher than planar chiral structures. It also amplifies cysteine enantiomer chiral signals by three orders of magnitude, showcasing great potential in high-sensitivity chiral sensing and

marking a breakthrough in intrinsic chiral metamaterial preparation. In parallel, the Agustin Mihi's team adopted high-throughput nanoimprint lithography (NIL) combined with phase-change material deposition to fabricate reconfigurable, temperature-resilient chiral metasurfaces (Figs. 5(d) and 5(e)) [60]. This methodology addresses traditional top-down limitations of low throughput, poor scalability, and incompatibility with phase-change materials, enabling large-area, high-efficiency fabrication of reconfigurable chiral structures. The resulting metasurfaces can switch chiroptical activity between visible and near-infrared regions,

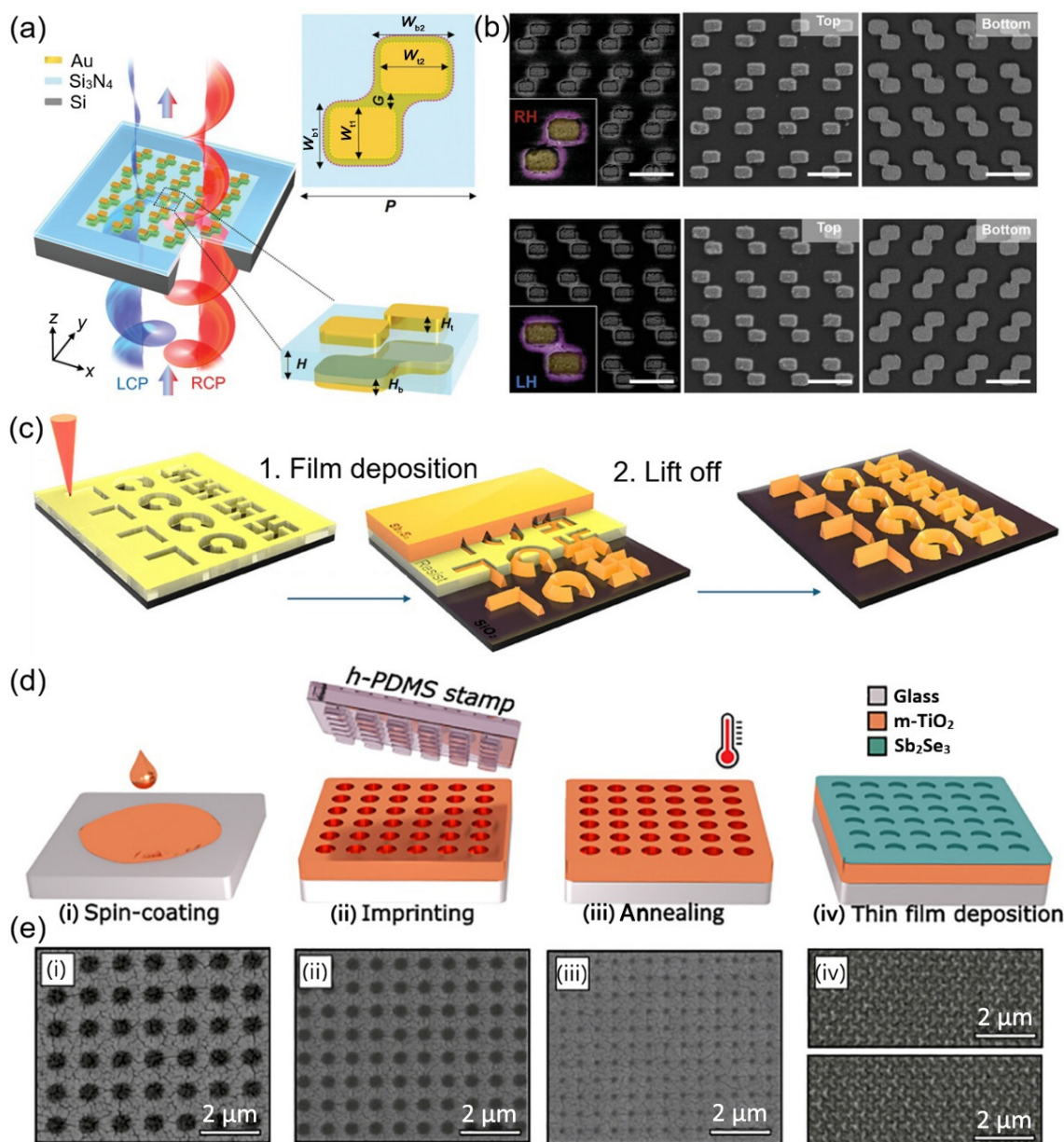


Figure 5 (a) Schematic of air-suspended chiral bilayer metasurface; (b) top and 3D views of the meta-atom (top and bottom insets, respectively). Reproduced with permission from Ref. [59], © Wiley-VCH GmbH 2022. (c) Schematic fabrication strategy of ICMMs via precise regulation of gradually reduced mask aperture during thin-film deposition. Reproduced with permission from Ref. [55], © Wiley-VCH GmbH 2025. (d) Flowchart summarizing the key fabrication steps; (e) top-view SEM images of various devices fabricated and optically characterized in this work. Reproduced with permission from Ref. [60], © de Ruiz de Galarreta, C. et al. 2026. Advanced Science published by Wiley-VCH GmbH.

exhibit excellent temperature resilience (withstanding phase change high temperatures), and offer tunable spectral band switching/amplitude modulation in the near-to-mid infrared-reflecting the top-down method's advantage in large-scale, functionalized chiral structure fabrication and providing a universal, scalable platform for nanophotonic devices.

In essence, these representative top-down methodologies strictly adhere to the core principle of introducing chiral structures through physical or chemical processing of bulk materials or thin films, with high precision and controllability as their defining characteristics. Common limitations include high equipment investment, more complex fabrication processes compared to the bottom-up self-assembly method, low throughput of the one-step EBL technique,

and the requirement for high-precision mold fabrication in NIL. Collectively, these studies have enriched the top-down technical system for chiral inorganic thin films, expanded its applications in high-sensitivity sensing, high-performance photonics, and large-scale reconfigurable devices, and provided critical technical support for the fabrication of high-precision, high-performance, and practically applicable chiral inorganic thin films.

On the basis of the summary of preparation methodologies, classifying chiral inorganic thin films based on the bottom-up self-assembly method, solvothermal method, and top-down method facilitates a systematic understanding of the intrinsic relationship between their preparation methodologies, microstructures, and chiral properties (Table 1). Each preparation methodology

Table 1 Classification and comparison of chiral inorganic thin films based on typical fabrication methods

Fabrication method	Principle & features	g_{CD}	g_{lum}	Representative materials
Bottom-up self-assembly	Chiral precursors self-assemble; high chiral order	0.01–0.3	0.05–1.3	Chiral Au NPs film [21, 23, 36], Au NR film [21, 45], CdS NR film [43], NiMoO ₄ film [44] etc.
Solvothermal method	High temp/pressure crystallization; high crystallinity	0.02–0.25	10 ^{−3} –0.4	Chiral TiO ₂ film [54], ZnO [53] film, Au film [48], Ag film [46, 61], Fe ₃ O ₄ film [29, 49], etc. [26, 47, 48, 51]
Top-down method	Etching/patterning; high precision	0.02–0.5	10 ^{−3} –0.7	Chiral Si film [59], Au film [58, 62, 63], Al ₂ O ₃ film, etc. [55–57]

possesses unique advantages and applicable scenarios; moreover, the cross-combination of different methodologies further provides a new approach for the design and development of novel multifunctional chiral inorganic thin films. Against this backdrop, in the following sections, the core properties and practical applications of chiral inorganic thin films will be further elaborated based on this established classification system.

3 Applications

3.1 Chiral sensing and enantiomeric recognition

Chiral sensing and enantiomeric recognition imaging are the most mature and widely studied applications of chiral inorganic thin films, leveraging their unique chiroptical responses (e.g., CD, optical rotatory dispersion, chiral surface plasmon resonance) for high-sensitivity detection and visualization of chiral molecules, enantiomers, and chiral biomolecules [36, 48]. Their core advantage is amplifying weak chiral signals via structural design and assembly regulation, overcoming traditional limitations (low sensitivity, poor selectivity, complex operation) to enable label-free, real-time, high-throughput detection.

The Ki Tae Nam's team constructed ordered chiral films via self-assembly of chiral Au building blocks, using interparticle collective interactions to amplify chiral signals for high-sensitivity enantioselective sensing (Figs. 6(a)–6(c)) [36]. Ordered arrays induce strong electromagnetic coupling, generating a collective CD signal 10–100 times stronger than individual nanoparticles. Chiral target molecules disrupt assembly equilibrium via competitive binding, causing 5–20 nm CD peak shifts or 20%–50% intensity changes, enabling enantiomer identification with a 10^{−9} mol·L^{−1} detection limit. Mild conditions and high amplification efficiency make it suitable for low-molecular-weight chiral species (e.g., chiral drugs, amino acids) detection. Complementing this signal amplification approach, the Qingfeng Zhang's team integrated chiral plasmonic assembly with surface-enhanced Raman scattering (SERS) for high-selectivity, ultra-high-sensitivity chiral sensing (Figs. 6(d)–6(f)) [30]. By regulating chiral ligand coverage (30%–90%) on plasmonic nanoparticles, they tuned chiral SERS signals; specific chiral interactions (dependent on configuration matching) induce a 3–5:1 L-/D-enantiomer characteristic peak ratio. Plasmonic enhancement (factor up to 10⁶) achieves a 10^{−12} mol·L^{−1} detection limit, expanding applications to chiral small molecules, polymers, and biomolecules. In parallel, the Hua Kuang's team developed a chiral plasmonic assembly combined with optoionic coupling to construct dual-mode chiral sensing membranes for sensing and enantiomer recognition imaging (Figs. 6(g) and 6(h)) [23]. Self-assembled chiral films integrate polarization sensitivity and optoionic properties: incident circularly polarized light modulates ion transport (10%–30% conductivity change), while chiral target binding alters both polarization signals (5°–15° rotation) and conductivity for high-accuracy real-time detection.

Imaging with 100–200 nm spatial resolution visualizes enantiomer distribution in complex systems (e.g., biological tissues).

A comprehensive analysis of the studies reveals that their core methodologies are closely related to the preparation methods of chiral inorganic thin films, and each has distinct characteristics and application orientations. The supramolecular coordination-driven self-assembly combined with collective CD signal amplification methodology focuses on chiral signal amplification, with the advantages of mild conditions and high sensitivity, suitable for high-throughput detection of low-molecular-weight chiral species; the chiral plasmonic assembly combined with SERS methodology emphasizes the integration of chiral recognition and SERS enhancement, achieving high selectivity and ultra-high sensitivity, applicable to trace chiral molecule detection; the chiral plasmonic assembly combined with optoionic coupling methodology realizes dual-mode sensing and imaging, with high spatial resolution, suitable for the visualization of chiral molecule distribution. These methodologies fully reflect the diversity and advancement of chiral sensing and enantiomer recognition imaging technologies based on chiral inorganic thin films, and their common core is to utilize the chiral structure of the thin film to achieve specific interaction with target enantiomers, and amplify the weak chiral signal through structural regulation or functional integration, thereby overcoming the limitations of traditional chiral sensing methods. Collectively, these methodologies provide important technical support for the development of high-performance chiral sensing and imaging devices, and promote the practical application of chiral inorganic thin films in environmental monitoring, food safety, and clinical diagnosis.

3.2 Chiral polarization imaging

Chiral polarization is a core application field of chiral inorganic thin films, focusing on the precise regulation, manipulation, and conversion of CPL. It plays an irreplaceable role in quantum optics, optoelectronic devices, 3D display, and optical information encryption. Chiral inorganic thin films overcome the inherent limitations of traditional organic chiral materials poor thermal stability, low optical asymmetry factor, and narrow spectral range by virtue of their adjustable chiral micro/nanostructures, excellent environmental stability, and strong chiroptical responses. The core of chiral polarization technology lies in designing chiral thin film structures that selectively interact with LCP and RCP circularly polarized light, thereby enabling CPL selective transmission, reflection, conversion, and amplification [63, 64].

The Nicholas A. Kotov's team realizes extreme polarization regulation through the composite assembly of achiral inorganic nanomaterials (Figs. 7(a) and 7(b)) [40]. The core logic of this methodology is to construct chiral-like polarization response systems by precisely patterning achiral inorganic nanomaterials and regulating their spatial arrangement, thereby achieving extreme polarization optics performance that is difficult to achieve with

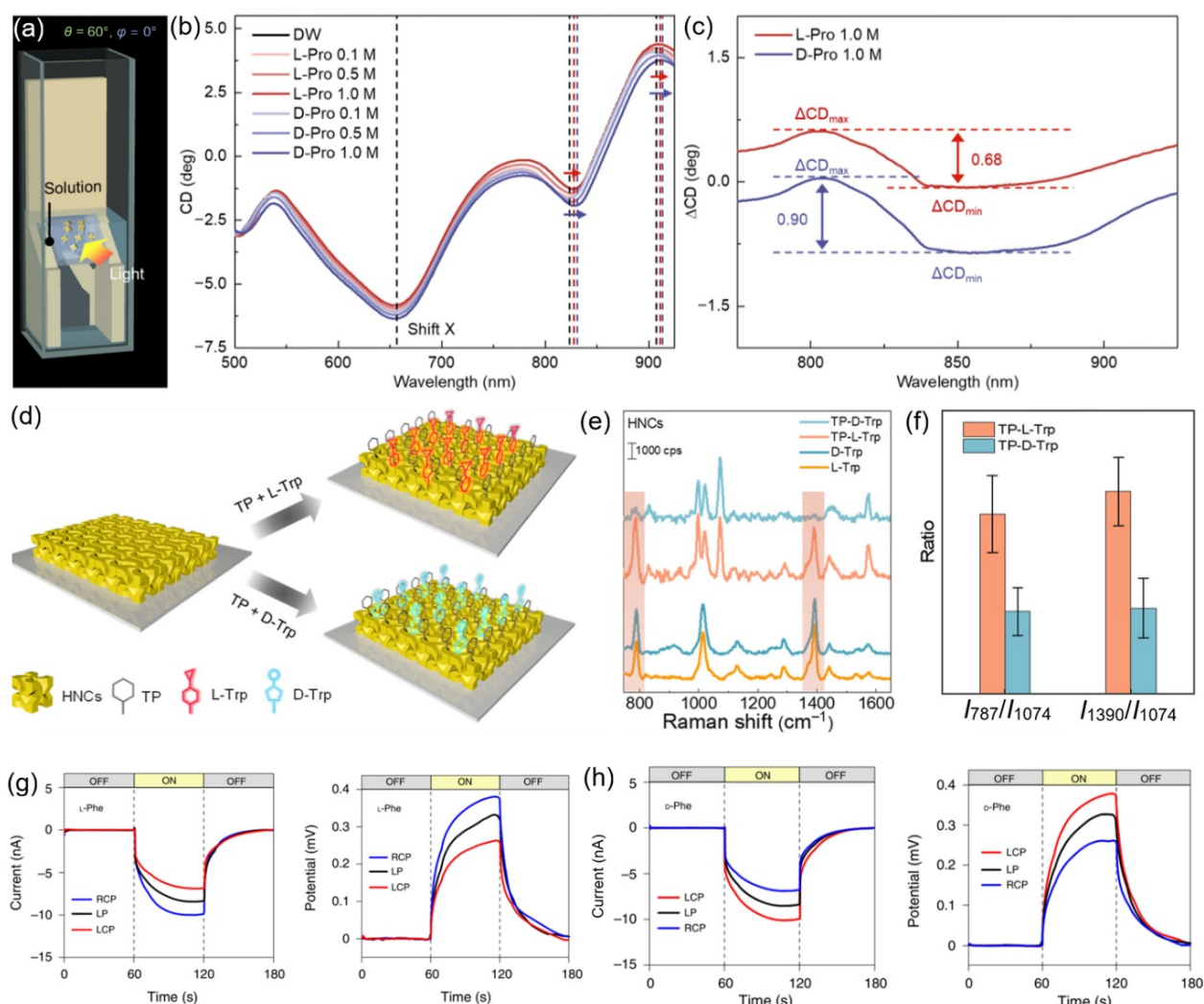


Figure 6 (a) Schematic of sensing experiments in a cuvette system; (b) full-range CD spectra of 2D helicoid crystals in deionized water, 0.1–1.0 M L-Proline (Pro) and D-Pro solutions; (c) collective CD variations induced by 1.0 M L-Pro and D-Pro. Reproduced with permission from Ref. [36], © Nature Publishing Group 2022. (d) Construction of an enantioselective recognition system with thiophenol (TP) as the molecular spacer; (e) SERS spectra of L/D-Tryptophan (Trp) (2.65×10^{-4} mM) without and with TP; (f) comparisons of I_{787}/I_{1074} and I_{1390}/I_{1074} intensity ratios for L-Trp and D-Trp. Peaks at 787 and 1390 cm^{-1} are assigned to Trp, and 1074 cm^{-1} from TP serves as the internal standard. Reproduced with permission from Ref. [30], © American Chemical Society 2025. (g) Temporal photocurrent responses of photosensitive membranes incorporated with L-Phenylalanine (Phe)-NPs and (h) D-Phe-NP nanofilms. Reproduced with permission from Ref. [23], © Nature Publishing Group 2022.

traditional chiral structures. A key feature of this methodology is that it realizes extreme polarization optics performance (e.g., polarization extinction ratio up to 1000:1, polarization rotation angle up to 90°) without relying on intrinsic chiral structures, overcoming the bottleneck that traditional chiral thin films are difficult to achieve ultra-high polarization contrast. The key technical parameters include the precise control of the nano-groove pattern (to regulate the spatial arrangement of achiral nanoparticles), the optimization of the nanoparticle mixing ratio (to balance plasmonic and dielectric properties), and the annealing process (to ensure the stability of the composite thin film). This methodology combines the high precision of top-down patterning with the flexibility of composite assembly, and its advantage lies in the adjustable polarization performance, excellent thermal stability, and low preparation cost, making it suitable for extreme polarization optics devices such as high-contrast polarizers and polarization modulators in quantum communication and optical detection.

Complementing this achiral-based polarization regulation

strategy, the Joon Hak Oh's team developed a self-assembly combined with plasmonic coupling enhancement methodology, focusing on achieving a gigantic chiroptical response to enable high-efficiency polarized emission and high-security information encryption (Figs. 7(c)–7(f)) [63]. The core approach is to construct chiral plasmonic thin films via self-assembly of chiral plasmonic nano units, leveraging plasmonic coupling effects between nano units to amplify chiroptical responses—thus meeting the application requirements of polarized emission and information encryption. For polarized emission, the chiral plasmonic thin film is integrated with a light-emitting layer (e.g., quantum dots), and its gigantic chiroptical response selectively enhances LCP or RCP light emission (enhancement factor up to 100), realizing high-purity polarized emission. For information encryption, the chiral plasmonic thin film exhibits distinct polarization responses to LCP and RCP light; encrypted information can only be decoded by adjusting the incident light polarization direction, ensuring high security. Collectively, these approaches circumvent the inherent drawbacks of traditional organic and chiral thin film materials,

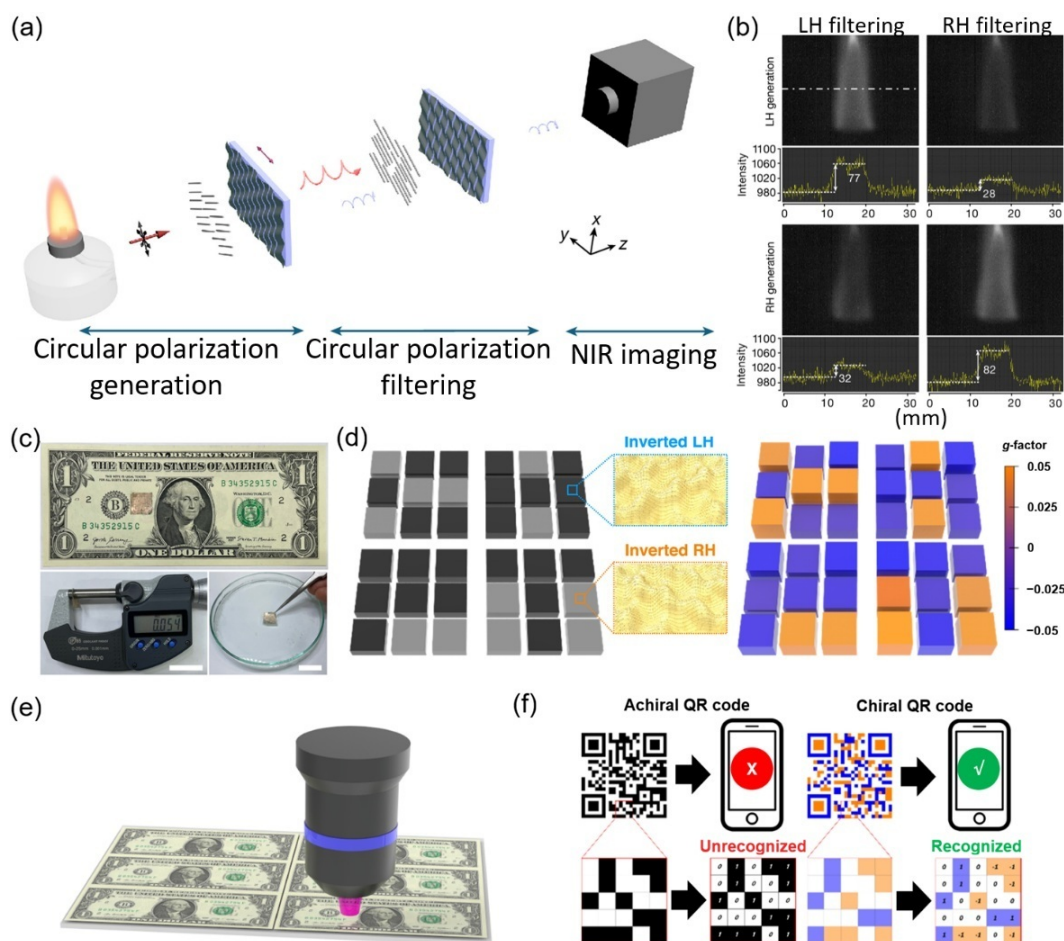


Figure 7 (a) Schematics of circularly polarized optical imaging with LH and H composites; (b) images and intensity profiles of LH- and H-polarized flame captured by a NIR camera integrated with M2-composited $\text{Ti}_3\text{C}_2\text{T}_x$ and Ag nanowire layers for circular polarization filtering. Reproduced with permission from Ref. [40], © Lu, J. et al, under exclusive licence to Springer Nature Limited 2024, corrected publication 2024. (c) Chiral QR code on a \$1 bill; its thickness was measured with a micrometer; (d) schematic diagram; Schematic illustrating of potential applications in (e) anti-counterfeiting and (f) next-generation chiral QD codes. Reproduced with permission from Ref. [63], © Lee, Y. H. et al. 2023.

complementing each other in performance and application scenarios. They offer novel design principles and viable technical routes for the development of high-performance chiroptical devices and secure optical information systems.

3.3 Chiral electrocatalytic reduction

Chiral electrocatalytic reduction is an emerging, promising application field of chiral inorganic thin films, integrating chiral recognition with the excellent electrocatalytic performance of inorganic materials to realize enantioselective reduction of prochiral molecules (achiral molecules that form chiral products after reduction). It is valuable for chiral drug synthesis, chiral fine chemicals, and intermediates, enabling direct acquisition of high enantiomeric excess (ee) chiral products without complex separation, reducing costs and pollution [32]. The core lies in the synergy of chiral recognition and electrocatalysis: the film's chiral structure selectively adsorbs prochiral enantiomers, while inorganic components provide active sites to guide asymmetric reduction [33, 65–67]. This section systematically analyzes core methodologies, explores connections with chiral polarization, and reveals their mechanisms and application advantages.

The Peng-peng Wang's team developed a solvothermal-induced symmetry-breaking assembly combined with spin polarization

regulation methodology (Figs. 8(a)–8(c)) [50]. Though focused on water oxidation in its title, its core chiral preparation and electrocatalytic regulation are fully applicable to chiral electrocatalytic reduction. Innovatively introducing spin control, it breaks reliance on traditional chiral ligands. Key parameters: solvothermal temperature/time (controlling crystal growth/chiral structure), nickel doping ratio (balancing spin polarization/electrocatalytic activity), and chiral ligand type (determining handedness). This approach expands chiral electrocatalysis regulation and provides a new route for spin-controlled chiral reduction. Complementing this spin-regulated strategy, the Yuxi Fang's team integrated chiral recognition with high electrocatalytic activity for nitrite reduction (Fig. 8(d)–8(f)) [47]. This methodology achieves high-efficiency electrocatalytic reduction of nitrite to ammonia, with a conversion rate of up to 92% and an NH_3 yield of $8.5 \text{ mmol} \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$, which is significantly higher than that of achiral Pd films. Additionally, the chiral structure endows the film with excellent anti-poisoning performance, as the chiral adsorption site can reduce the adsorption of impurity ions, ensuring long-term electrocatalytic stability. Furthermore, the Shunai Che's team used chiral nanostructured Ag films to address low multicarbon product (ethanol, ethylene) selectivity in CO_2 electroreduction, realizing chiral-dependent selectivity (Fig. 8(g)–8(j)) [33]. The core

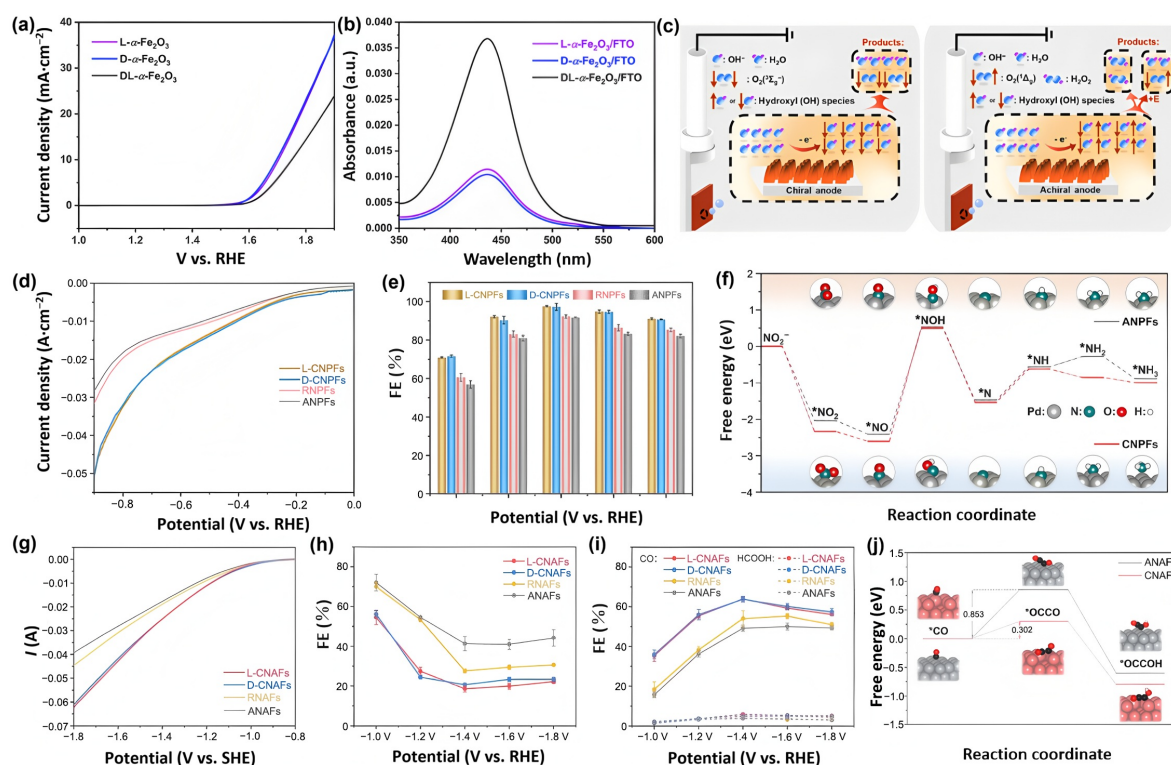


Figure 8 (a) LSV curves of chiral and achiral $\alpha\text{-Fe}_2\text{O}_3/\text{FTO}$ electrodes; (b) UV-vis absorption spectra of H_2O_2 production after 30 min OER over chiral $\alpha\text{-Fe}_2\text{O}_3$; (c) spin-uncontrolled reaction pathways during OER. Reproduced with permission from Ref. [50], © Wiley-VCH GmbH 2025. (d) LSV curves. (e) NH_3 Faradaic efficiencies; (f) free energy diagrams NO_3RR on CNPFs and ANPFs surface. Reproduced with permission from Ref. [47], © Elsevier B.V. 2025. (g) LSV curves. (h) Faradaic efficiencies of H_2 . (i) FEs of $2e^-$ C_1 products (CO and HCOOH); (j) DFT calculations for the C-C coupling on CNAFs and ANAFs. Reproduced with permission from Ref. [33], © American Chemical Society 2024.

mechanism: chiral network structures induce asymmetric CO_2 adsorption/activation, guiding reactions toward multicarbon (not single-carbon) products. Template chiral configuration (L-/D-) determines selectivity (ethanol: 65%–70%, ethylene: 15%–20%). Combining top-down template fabrication with bottom-up Ag nanowire assembly, it provides a new strategy for CO_2 -to-multicarbon synthesis.

In this section, we have systematically categorized mainstream construction strategies, discussed the intrinsic correlation between chiral polarization and chiral electrocatalysis, and elaborated on catalytic mechanisms, technical merits and practical application prospects of such systems.

3.4 Chiral biomedical applications

Chiral inorganic thin films have broad application prospects in the biomedical field due to their good biocompatibility, stable chiral properties, and adjustable physical and chemical properties, mainly involving chiral drug delivery, chiral imaging, and chiral therapy. Among these, chiral regulation of cell interactions, bone regeneration, and implant integration has become a research hotspot, as the chirality of thin films can selectively mediate biological responses (e.g., cell adhesion, proliferation, immune regulation), improve the biocompatibility and functionality of biomedical materials, and solve key bottlenecks such as poor osseointegration of implants and insufficient bone regeneration [68–70]. The core of chiral biomedical applications based on chiral inorganic thin films lies in the enantioselective recognition between the chiral structure of the film and biological systems (cells, proteins, tissues), which guides specific biological behaviors and

achieves targeted regulation of physiological processes.

The Shunai Che's team adopts the solvothermal-induced chiral crystallization combined with cell response evaluation methodology, which focuses on exploring the enantioselective interaction mechanism between chiral hydroxyapatite (HA) thin films and cells, laying a foundation for the design of chiral biomedical materials with cell-specific recognition. Hydroxyapatite is the main component of natural bone and teeth, with excellent biocompatibility and osteoconductivity, and its chiral modification can further enhance its interaction with biological systems (Figs. 9(a) and 9(b)) [28]. The core mechanism of this methodology is enantioselective recognition between chiral HA films and cell surface receptors: The chiral structure of the HA film matches the chiral configuration of cell surface proteins (e.g., integrins), thereby regulating the adhesion and proliferation of different cell types. For example, L-chiral HA films significantly promote the adhesion and proliferation of osteoblasts (proliferation rate increased by 40%–50% compared with achiral HA films), while inhibiting the growth of fibroblasts, which is beneficial for reducing fibrous capsule formation around implants. This methodology combines solvothermal chiral preparation with biological evaluation, clarifying the enantioselective interaction mechanism between chiral inorganic thin films and cells, and providing a theoretical basis for the design of cell-specific chiral biomedical materials.

Complementing this cell-targeted research, the Hongjiang Ruan's team employs the bottom-up chiral self-assembly combined with implant surface modification methodology, which focuses on solving the problem of poor osseointegration of bone implants in osteoporotic environments by regulating enantioselective bone-

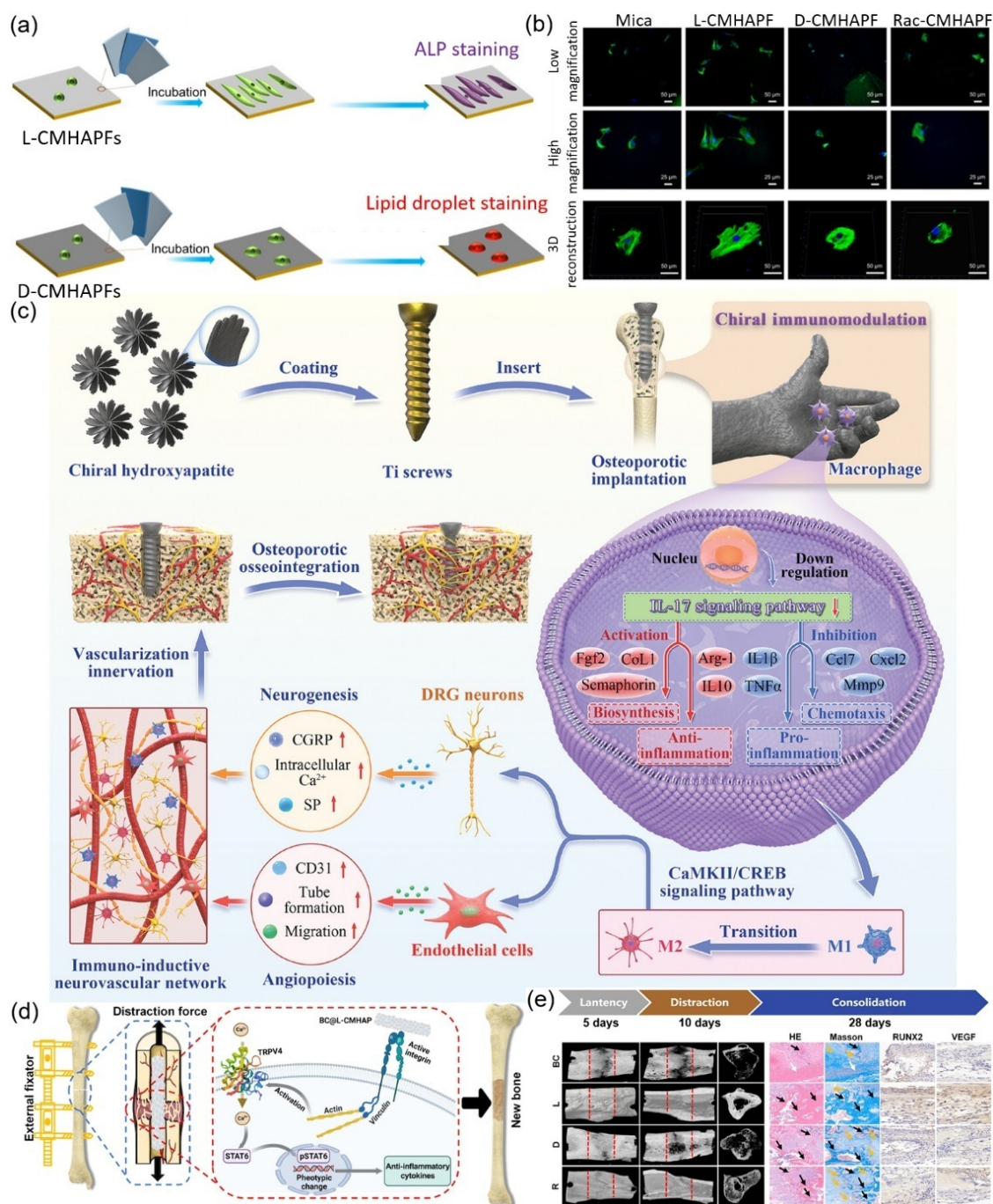


Figure 9 (a) Schematic of enantioselective interaction between cells and chiral hydroxyapatite films; (b) confocal images of Ad-MSCs cultured on different substrates. Reproduced with permission from Ref. [28], © American Chemical Society 2021. (c) Schematic of L-CHA-coated Ti regulating desired immunomodulation, enhanced neurogenesis and angiogenesis for improved osteoporotic osseointegration. Reproduced with permission from Ref. [69], © Yang, L. et al. 2024. Advanced Science published by Wiley-VCH GmbH. (d) Schematic of chirality regulating bone regeneration via mechanoreponse and immunoregulation; (e) 3D micro-CT images of the consolidation zone after 4 weeks (highlighting the most continuous callus formation in the L group; two red dotted lines delineate the regeneration site) and representative images of HE staining, Masson's staining, and immunohistochemical analysis of Runx2 and vascular endothelial growth factor. Reproduced with permission from Ref. [70], © American Chemical Society 2025.

implant interactions. This methodology integrates the advantages of bottom-up self-assembly in constructing ordered chiral structures and the biocompatibility of HA, realizing targeted improvement of osteoporotic osseointegration (Fig. 9(c)) [69]. This methodology realizes the application of chiral inorganic thin films in bone implant modification, providing a new strategy for improving osteoporotic osseointegration and expanding the practical

application of chiral biomedical materials. Building on this progress, the team further proposed a template-assisted chiral assembly methodology coupled with mechano-immune regulation, which innovatively uncovers the dual regulatory mechanism of chirality in bone regeneration-mechanoreponse and immunoregulation-offering a new approach for efficient bone regeneration (Figs. 9(d) and 9(e)) [70]. This methodology combines top-down template

fabrication with bottom-up chiral assembly, realizing precise regulation of the chiral structure and biological functions of thin films. This methodology reveals the multi-dimensional regulatory role of chirality in bone regeneration, providing a new theoretical and technical basis for the design of high-performance chiral bone regeneration materials.

The common core of the methodologies is to construct a chiral interface between inorganic thin films and biological systems, realize enantioselective recognition and interaction, and regulate specific biological behaviors, overcoming the limitations of traditional biomedical materials (poor targeting, insufficient biocompatibility, single regulatory function). Current challenges in this field include improving the long-term stability of chiral thin films in physiological environments, enhancing the precise regulation of chiral properties on biological responses, and realizing the clinical transformation of chiral biomedical materials. With the in-depth integration of chiral materials science and biomedical technology, chiral inorganic thin films are expected to become a new generation of biomedical materials, providing new technical approaches for cell regulation, bone regeneration, and implant modification.

4 Conclusion and outlook

In summary, chiral inorganic thin films have shown unique advantages and broad application prospects in chiral sensing and enantiomer recognition imaging, chiral polarization, chiral electrocatalytic reduction, and chiral biomedical applications. The development of these application fields is closely related to the preparation methods of chiral inorganic thin films, and the cross-combination of different preparation methods and application technologies will further promote the innovation and practical application of chiral inorganic thin films. However, there are still many unsolved problems in the research and application of chiral inorganic thin films, including limited control over chiral structure and uniformity, lack of deep understanding of chiral mechanism, challenges in practical application and industrialization, and lack of high-efficiency characterization and detection methods. These problems restrict the further development and practical application of chiral inorganic thin films.

In the future, the research focus will be on solving the above key technical problems and promoting the high-quality development of chiral inorganic thin films. Specifically, the future development directions will focus on four aspects: first, optimizing preparation methods and realizing precise regulation of chiral structure to improve the uniformity, chiral purity, and stability of thin films; second, deeply exploring the chiral mechanism and structure-activity relationship to provide theoretical guidance for the design and optimization of thin films; third, expanding application fields and promoting technological innovation to give full play to the functional advantages of chiral thin films in various frontier fields; fourth, improving practical application capability and industrialization level to promote the large-scale application of chiral inorganic thin films. With the continuous advancement of research and technology, chiral inorganic thin films will surely play a more important role in various fields and bring new opportunities for technological innovation and industrial development.

Data availability

All data needed to support the conclusions in the paper.

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Declaration of competing interest

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

Author contribution statement

T. W.: Formal analysis and conceptualization. H. L. W.: Methodology and data analysis. Z. Y. Z.: Review and editing. C. L. Z.: Review and editing. F. B.: Conceptualization, writing, and supervision. G. Y. W.: Conceptualization, writing, and funding acquisition. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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