

Regulation of heterogeneous multiphase structures by heterogeneous atoms to enhance polarization loss electromagnetic wave

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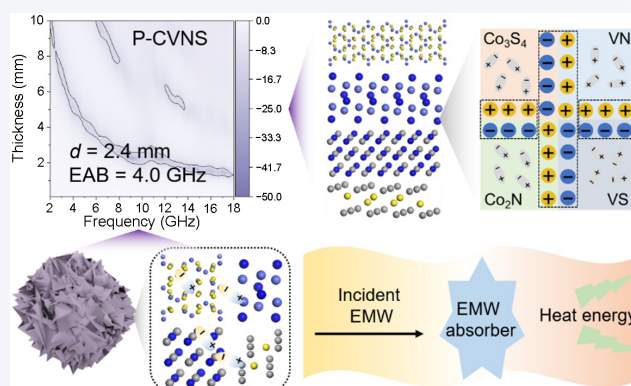
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ABSTRACT: Regulating interfacial charge behavior in multiphase heterostructures is crucial for achieving high-performance electromagnetic wave (EMW) absorption, yet the synergistic optimization of dielectric loss and impedance matching remains a major challenge. Herein, a phosphorus (P) atom doping strategy is proposed to modulate the interfacial properties of a multiphase $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ heterostructure. P-doping reconstructs the heterointerfaces, promotes charge redistribution, and generates abundant polarization centers, thereby simultaneously optimizing charge transport and polarization relaxation. Density functional theory (DFT) calculations further reveal the vital role of interfacial charge redistribution in boosting polarization behavior. Consequently, the optimized P-CVNS heterostructure achieves a reflection loss (RL) of -36.93 dB and an effective absorption bandwidth (EAB) of 4.0 GHz at a matching thickness of 2.4 mm. This work reveals the pivotal role of heteroatom-doped interface engineering in optimizing EMW absorption and presents a scalable strategy for designing high-performance absorbers.

KEYWORDS: heteroatom doping, interfacial charge transfer, polarization loss, electromagnetic wave (EMW) absorption



1 Introduction

The rapid proliferation of electronic devices and wireless communication technologies has led to increasing electromagnetic pollution, posing a serious threat to the operational stability of electronic systems [1–3]. In recent years, researchers have developed EMW absorbing materials through the rational design of dielectric/magnetic components, construction of hierarchical structures, and fabrication of heterogeneous interfaces [4, 5]. However, these strategies, when employed individually or in simple combinations, often result in impedance mismatch, making it difficult to achieve efficient EMW dissipation. Therefore, developing composite strategies capable of precisely regulating charge behavior and polarization characteristics is crucial for

overcoming the performance bottlenecks of high-performance EMW absorbing materials.

Previous studies have shown that the rational design of heterostructures can effectively enhance EMW attenuation [6]. The underlying mechanism relies on constructing abundant heterogeneous interfaces, which facilitate interfacial charge accumulation and polarization relaxation, thereby boosting EMW dissipation capacity. To further intensify these interfacial effects, researchers have employed strategies such as phase modulation, interface engineering, and multiphase structural design to increase interface density and optimize interfacial electronic interactions. Although these strategies effectively improve dielectric loss and EM attenuation, active control over interfacial electronic behavior remains insufficient. Through tailored interface design, electronic interactions between adjacent phases can be tuned to regulate dielectric loss while maintaining good impedance matching [7, 8]. However, excessive interfacial electron migration often leads to increased conduction loss, leading to impedance mismatch. Therefore, rationally regulating interfacial electronic behavior to achieve a synergistic balance between conduction loss and polarization relaxation in complex multiphase systems remains a key challenge.

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Heteroatom doping serves as an effective approach to modulate the electronic structure of materials and induce charge redistribution. By incorporating atoms with distinct electronegativities and bonding characteristics, researchers can efficiently regulate the local electron density and chemical environment, leading to the formation of asymmetric charge distributions and polar structures. Among various dopants, P is particularly attractive due to its moderate electronegativity and its ability to interact strongly with both metallic and non-metallic elements. The incorporation of P atoms not only modulates band alignment and facilitates charge transfer but also introduces defect states and localized polarization, thereby enhancing polarization loss processes. Studies have demonstrated that heteroatom engineering can effectively regulate defect states, charge distribution, and electron transport, thereby enhancing EMW absorption performance. Researchers have achieved enhanced EM attenuation through P doping, anion-mediated interaction engineering, and transition metal substitution [9–11]. Nevertheless, the role of heteroatom doping in controlling the interfacial charge-polarization coupling within multiphase heterostructures has yet to be systematically elucidated. Previous studies have established heteroatom doping and hierarchical microstructure engineering as effective strategies for enhancing EMW absorption performance [12–14]. Heteroatoms facilitate charge redistribution, generating localized polarization centers and promoting synergistic polarization relaxation, thereby enhancing dielectric loss. Concurrently, the synergistic tailoring of hierarchical hollow microstructures and multiphase heterointerfaces further diversifies the EMW dissipation mechanisms [15].

Herein, we propose a heteroatom engineering strategy to modulate the interfacial charge transfer and polarization relaxation in phase-engineered multiphase heterostructures. Through a controlled phase evolution process, a multiphase architecture consisting of $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ (CVNS) was rationally constructed. Subsequently, P dopants were introduced to regulate the electronic structure of the heterointerfaces. The coexistence of metallic, nitride, and sulfide phases generates abundant multi-scale interfaces, while P doping induces significant charge redistribution and built-in electric fields at these boundaries. Consequently, interfacial and dipole polarization are significantly enhanced. More importantly, the optimized electronic structure effectively balances conduction loss and impedance matching.

Ultimately, the resulting P-CVNS heterostructures deliver exceptional EMW attenuation capabilities. This study provides new insights into the coupling between interfacial charge transfer and polarization in heterogeneous structures.

2 Experimental section

2.1 Materials

Ammonium metavanadate (NH_4VO_3), cobalt(II) chloride hexahydrate ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$), lithium hydroxide (LiOH), and thioacetamide ($\text{C}_2\text{H}_5\text{NS}$, TAA) were purchased from Shanghai Macklin Biochemical Technology Co., Ltd. Deionized water was used throughout the experiments.

2.2 Preparation of $\text{Co}_3\text{V}_2\text{O}_8$

Typically, 0.37 g of NH_4VO_3 and 64 mL of deionized water were mixed and stirred at 80 °C for 30 min. 0.0718 g of LiOH and

0.152 g of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ were mixed and stirred for 10 min, then combined with the NH_4VO_3 solution. The mixture was heated at 100 °C for 8 h to obtain $\text{Co}_3\text{V}_2\text{O}_8$.

2.3 Preparation of CVO, P-CVO, CVN, and P-CVN

To synthesize $\text{Co}_3\text{O}_4/\text{V}_3\text{O}_4$ (CVO), the obtained $\text{Co}_3\text{V}_2\text{O}_8$ precursor was heated to 600 °C in a tube furnace under a flowing Ar atmosphere at a heating rate of 5 °C/min and held for 2 h. For the synthesis of P- $\text{Co}_3\text{O}_4/\text{V}_3\text{O}_4$ (P-CVO), NaH_2PO_2 and $\text{Co}_3\text{V}_2\text{O}_8$ were placed in two separate crucibles with a mass ratio of 10:1 (with NaH_2PO_2 situated upstream), and then calcined under identical conditions in Ar. Similarly, CoN/VN (CVN) and P-CoN/VN (P-CVN) were prepared by replacing the Ar atmosphere with flowing NH_3 , while keeping all other parameters constant.

2.4 Preparation of CoS_2/VS_2

In a typical procedure, 0.06 g of $\text{Co}_3\text{V}_2\text{O}_8$, 0.2 g of thioacetamide (TAA), and 0.2 g of LiOH were dispersed in 60 mL of deionized (DI) water under vigorous stirring. The homogeneous mixture was transferred into a Teflon-lined stainless-steel autoclave and hydrothermally treated at 120 °C for 16 h. After naturally cooling to room temperature, the precipitates were collected by filtration, washed thoroughly with DI water and anhydrous ethanol, and dried overnight to obtain the CoS_2/VS_2 precursor.

2.5 Preparation of CVS, P-CVS, CoVNS, and P-CVNS

To obtain CoS_2/VS_2 (CVS) and CVNS, the CoS_2/VS_2 precursor was calcined at 600 °C for 2 h at a heating rate of 5 °C/min under Ar and NH_3 atmospheres, respectively. For the P-doped counterparts, NaH_2PO_2 was introduced as the P source and placed upstream relative to the CoS_2/VS_2 precursor at a mass ratio of 10:1. The subsequent phosphorization processes were conducted under Ar and NH_3 atmospheres to yield P-CVS and P-CVNS, respectively.

2.6 Characterization

The crystal structure of the samples was characterized using X-ray diffraction (XRD, wavelength $\lambda = 0.15418$ nm). Raman spectroscopy was conducted at 532 nm with a Renishaw InViaPlus Raman system equipped with a 50 mW DPSS laser. Surface chemical analysis of elemental composition and chemical environment was performed via X-ray photoelectron spectroscopy (XPS) on a 250Xi spectrometer with an aluminum K α -ray source. The microstructure, morphology, elemental distribution, and interplanar spacing of the samples were examined using field emission scanning electron microscopy (SEM, JEOL JSM-7800F) and transmission electron microscopy (TEM, JEOL JEM-2100). Electrochemical measurements were performed in a standard three-electrode setup with a platinum sheet as the counter electrode, an Ag/AgCl reference electrode, and a glassy carbon working electrode.

Using a vector network analyzer (N5222A; Agilent Technologies, USA), the electromagnetic parameters of each sample were measured across frequencies from 2 to 18 GHz using coaxial transmission lines. The samples' EMW absorption characteristics were also calculated. Each sample was mixed with molten paraffin wax at a 20% loading ratio to reach a total mass of 70 mg. The mixture was then pressed into a ring-shaped mold to form a ring-shaped sample (outer diameter: 7.0 mm, inner diameter: 3.04 mm, thickness: 2 mm). The reflection loss was calculated from the measured electromagnetic parameters using the following equation (Eqs. (1) and (2)) [16]

$$RL \text{ (dB)} = 20 \lg \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (1)$$

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left(j \frac{2\pi f d}{c} \sqrt{\mu_r \epsilon_r} \right) \quad (2)$$

where Z_{in} and Z_0 represent the input impedances of the absorber and free space, respectively. ϵ_r and μ_r denote the complex permittivity and complex permeability of the absorber; d is the sample thickness; f is the frequency; c is the speed of light in free space.

3 Result and discussion

Figure 1(a) illustrates the preparation process for cobalt-vanadium-based multiphase heterostructures regulated by a heteroatom engineering strategy. First, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ prism precursors were synthesized through a one-step hydrothermal reaction using cobalt chloride hexahydrate and NH_4VO_3 , with LiOH as the structure-directing agent. Subsequently, TAA-assisted sulfidation and ammonia annealing were sequentially performed to regulate the phase composition and defect structures. Finally, NaH_2PO_2 was employed as the P source for phosphorization. During the annealing process, NaH_2PO_2 thermally decomposed to generate P-containing gaseous species, which diffused to the precursor surface

and gradually penetrated into the lattice through thermally activated diffusion. The incorporated P atoms partially substitute lattice sites and form Co-P and V-P bonds, leading to local lattice distortion, defect generation, and interfacial reconstruction. As a result, a P-doped cobalt-vanadium multiphase heterostructure (P-CVNS) with abundant heterogeneous interfaces was successfully obtained. XRD results confirm the transformation of the cobalt-vanadium precursor into a multiphase heterostructure (Figs. 1(b) and 1(c)). After phosphidation, the main diffraction peaks of each sample remain unchanged, with only slight peak shifts and broadening, indicating the successful incorporation of P atoms into the lattice and the induced local lattice distortion [17,18]. Figure 1(d) displays the crystal structure model of the CVNS components. The differences in electrical conductivity, band structure, and electronegativity among the constituent phases are expected to facilitate interfacial charge transfer and induce built-in electric fields, thereby contributing to EMW attenuation.

The morphological evolution of cobalt-vanadium-based materials treated under different atmospheres was systematically characterized using SEM. The $\text{Co}_3\text{V}_2\text{O}_8$ precursor obtained via hydrothermal synthesis was annealed in an argon atmosphere, resulting in the formation of Co-V oxides that appeared as irregularly aggregated micron-sized particles (CVO, Fig. 1(e)). Upon nitridation in an ammonia (NH_3) atmosphere, these particles largely retained the pseudo-hexagonal prismatic structure of the

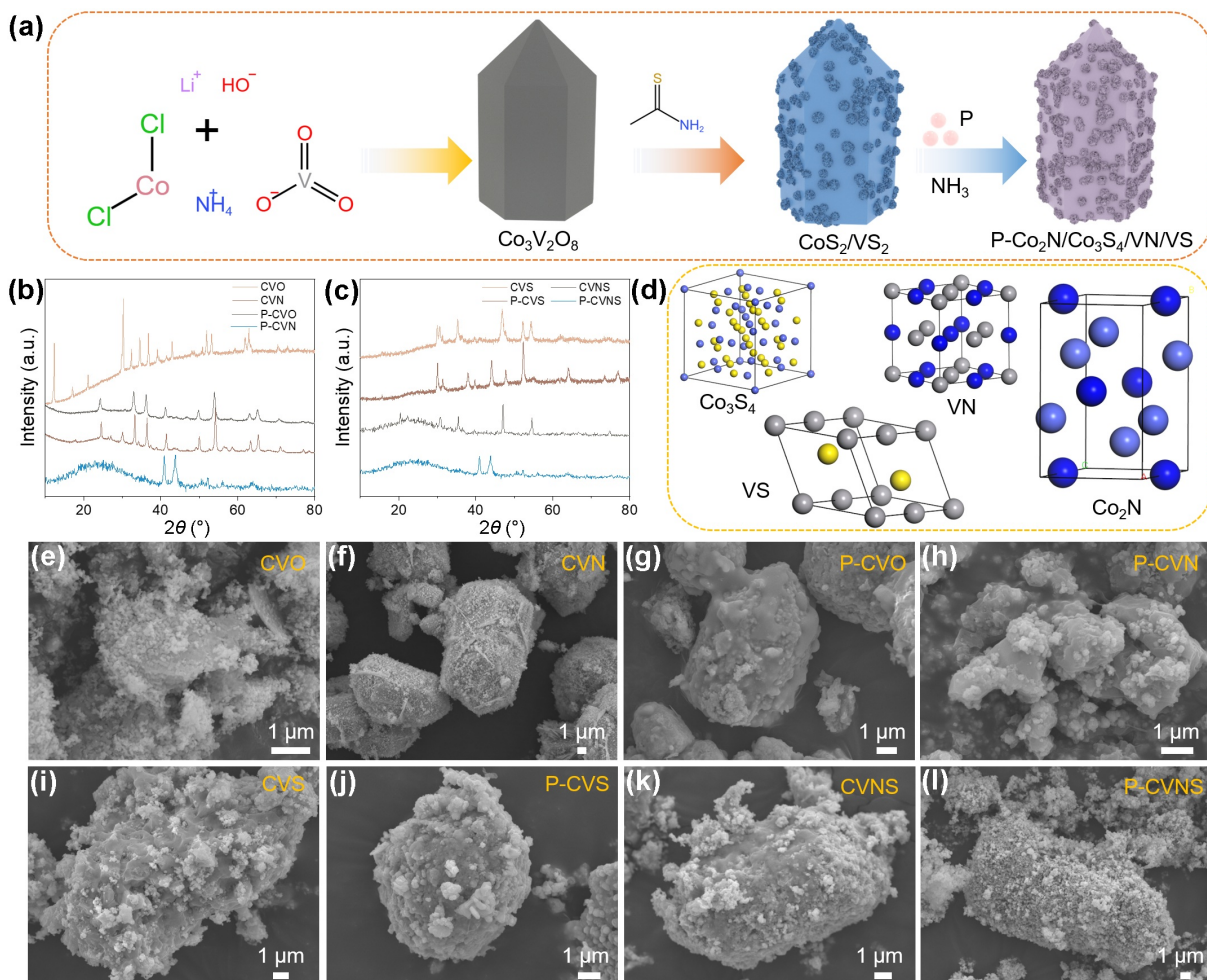


Figure 1 (a) Preparation flowchart of P-CVNS. (b) and (c) XRD patterns of the samples. (d) Crystal structure diagrams of the P-CVNS components. (e)–(l) SEM images of the samples.

starting material, while their surfaces were uniformly covered with nanoscale grains (Fig. 1(f)). This suggests that nitridation promotes surface atomic rearrangement and defect generation without disrupting the original framework. Notably, the introduction of P during the annealing process triggered significant morphological reconfiguration and densification. Both P-CVO and P-CVN exhibited continuous and dense coating layers on the particle surfaces (Figs. 1(g) and 1(h)). Some localized regions exhibited smooth and compact areas induced by sintering, accompanied by high-density nanoscale protrusions distributed across the substrate. For the sulfidated samples, the product obtained via sulfidation followed by Ar annealing maintained the pseudo-prismatic framework, with surfaces composed of loosely assembled nanoparticles, resulting in a rough and porous morphology (CVS, Fig. 1(i)). Upon co-modification with P, the structure evolved toward a more compact state, forming aggregated structures with micron-sized secondary particles anchored to the surface (P-CVS, Fig. 1(j)). This was accompanied by a general increase in particle size, indicating enhanced sintering effects and prominent nucleation-aggregation phenomena. For the sulfur and nitrogen co-treated sample, the particle surfaces exhibited a porous and rough structure composed of nanoscale grains (CVNS, Fig. 1(k)). Following P incorporation, the original particle framework remained intact, while a more uniform nanoscale coating layer formed on the surface (P-CVNS, Fig. 1(l)). The resulting morphology exhibited a rough and porous architecture, providing a larger exposed surface area that facilitates interfacial polarization and multiple scattering. EDS elemental mapping analysis of the P-CVNS sample confirmed the uniform distribution of Co and V, as well as heteroatoms including N, S, and P (Fig. S1 in the Electronic Supplementary Material (ESM)). All elements were uniformly

distributed throughout the micron-sized particles, with no observed segregation or aggregation.

The chemical states and bonding configurations of the P-CVNS sample were investigated via XPS. The XPS survey spectrum confirms the presence of Co, V, N, S, P, O, and C (Fig. 2(a)). The high-resolution N 1s spectrum can be deconvoluted into peaks corresponding to M–N, N–V, and N–O–V bonding configurations, indicating that nitrogen atoms were effectively incorporated into the lattice and coordinated with metal sites during the NH_3 annealing process (Fig. 2(b)) [19, 20]. The S 2p spectrum exhibits typical spin-orbit doublets of S 2p_{3/2} and S 2p_{1/2}, along with a S–O bonding signal, confirming the successful introduction of sulfur species and the formation of stable sulfur-containing phases (Fig. 2(c)) [21]. Meanwhile, the P 2p spectrum reveals the coexistence of P–O–V and V–P bonds, suggesting that P was successfully incorporated into the lattice while simultaneously forming stable V–P bonds (Fig. 2(d)) [22, 23]. High-resolution C 1s, O 1s, Co 2p, and V 2p spectra further confirm the existence of diverse bonding interactions between metallic and non-metallic elements, collectively demonstrating the formation of a chemically integrated and synergistically coupled system (Fig. S2 in the ESM). Raman spectroscopy further elucidates structural order and defect characteristics (Fig. S3 in the ESM). TEM analysis reveals pronounced microstructural variations arising from different post-treatment strategies. As shown in Fig. S4 in the ESM, P-CVS consists of closely packed nanoparticles embedded within a relatively loose porous framework, whereas the P-CVNS prepared under an NH_3 atmosphere possesses a more developed porous structure featuring abundant edge-like nanosheets. High-resolution TEM (HRTEM) images reveal the coexistence of crystalline and amorphous domains, generating abundant heterointerfaces. For P-

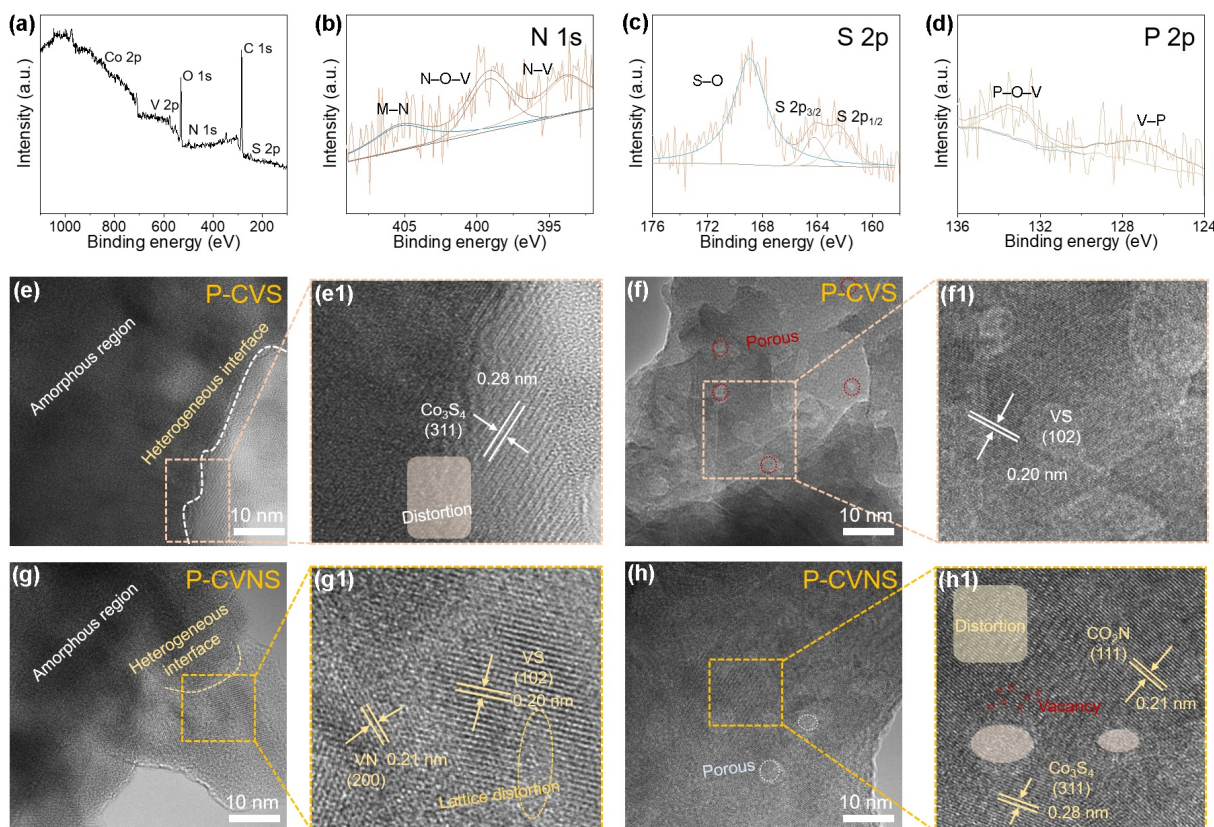


Figure 2 The XPS (a) total spectrum, (b) N 1s, (c) S 2p, and (d) P 2p spectra of P-CVNS. High-magnification TEM images of (e)–(f) P-CVS and (g)–(h) P-CVNS.

CVS, lattice fringes are indexed to the crystal planes of the corresponding phases, confirming successful phase formation and high crystallinity (Figs. 2(e)–2(f1)). In contrast, P-CVNS exhibits significant lattice distortions and defect features, including dislocations and defect-rich regions (Figs. 2(g)–2(h1)). These structural defects serve as effective polarization centers, promoting dipole and interfacial polarization under alternating electromagnetic fields. Importantly, lattice fringes remain clearly visible in P-CVNS despite the introduction of heteroatoms, indicating that P incorporation does not disrupt the fundamental crystal framework but rather induces controllable structural deformation. This observation is further corroborated by the selected area electron diffraction (SAED) patterns (Fig. S5 in the ESM).

The EMW absorption characteristics of the samples were systematically evaluated using a vector network analyzer [24–27]. As illustrated in Fig. 3(a), CVO exhibits poor EMW absorption performance, which may be attributed to its limited dielectric response and weak interfacial polarization. Following sulfidation and nitridation treatments, the EMW absorption performance is improved to some extent (Figs. 3(b)–3(g) and Fig. S6 in the ESM). This enhancement the introduction of heterogeneous phases, which strengthen interfacial polarization. However, the overall absorption capacity remains unsatisfactory. Notably, upon the incorporation of P, the EMW absorption performance is substantially enhanced. Among all samples, the P-doped multiphase heterostructure (P-CVNS) achieves the optimal performance, featuring an $RL_{\min}$ of approximately -36.93 dB and an EAB of 4.0 GHz (Fig. 3(h)). More importantly, this superior performance is maintained even at reduced matching thicknesses (Figs. 3(i) and 3(j); and Fig. S7 in the ESM). This remarkable improvement is primarily ascribed to the regulatory role of heteroatoms in interfacial charge-polarization coupling. P doping induces significant charge redistribution across

the Co–N, Co–S, VN, and VS interfaces, leading to the formation of localized polarization dipoles and built-in electric fields, which significantly enhance interfacial polarization [28–30]. Simultaneously, the multiple heterointerfaces constructed via phase engineering provide abundant polarization centers and facilitate multi-scale relaxation processes. A comprehensive comparison across all samples further demonstrates the superiority of P-CVNS, demonstrating that heteroatom-regulated interfacial electronic modulation is crucial for achieving high-performance electromagnetic absorbers (Figs. 3(k) and 3(l)). To further evaluate the competitiveness of this material, its EMW absorption performance is compared with that of representative transition-metal-based absorbers reported in recent years (Fig. S8 in the ESM). The P-CVNS heterostructure demonstrated competitive EMW absorption performance.

To further elucidate the underlying mechanisms governing the enhanced EMW absorption, the electromagnetic parameters of the samples were systematically investigated [31–33]. As shown in Figs. 4(a) and 4(b), the real part of the complex permittivity (ϵ') for all samples exhibits relatively stable characteristics [34]. However, ϵ' increases significantly following the phase evolution and P doping, particularly for the P-CVNS sample. This indicates an improvement in polarization and charge storage capacity, which is closely correlated with the heteroatom-induced electronic structure modulation. The imaginary part (ϵ''), representing the dielectric loss capacity, shows a substantial increase across a broad frequency range for the P-CVNS sample (Figs. 4(c) and 4(d)) [35, 36]. Notably, both ϵ' and ϵ'' exhibit several frequency-dependent fluctuations. These fluctuations originate from multiple dielectric relaxation processes associated with the abundant heterogeneous interfaces and P-induced defects. As the applied frequency varies, polarization centers with different relaxation times are successively activated, resulting in the characteristic upward and downward

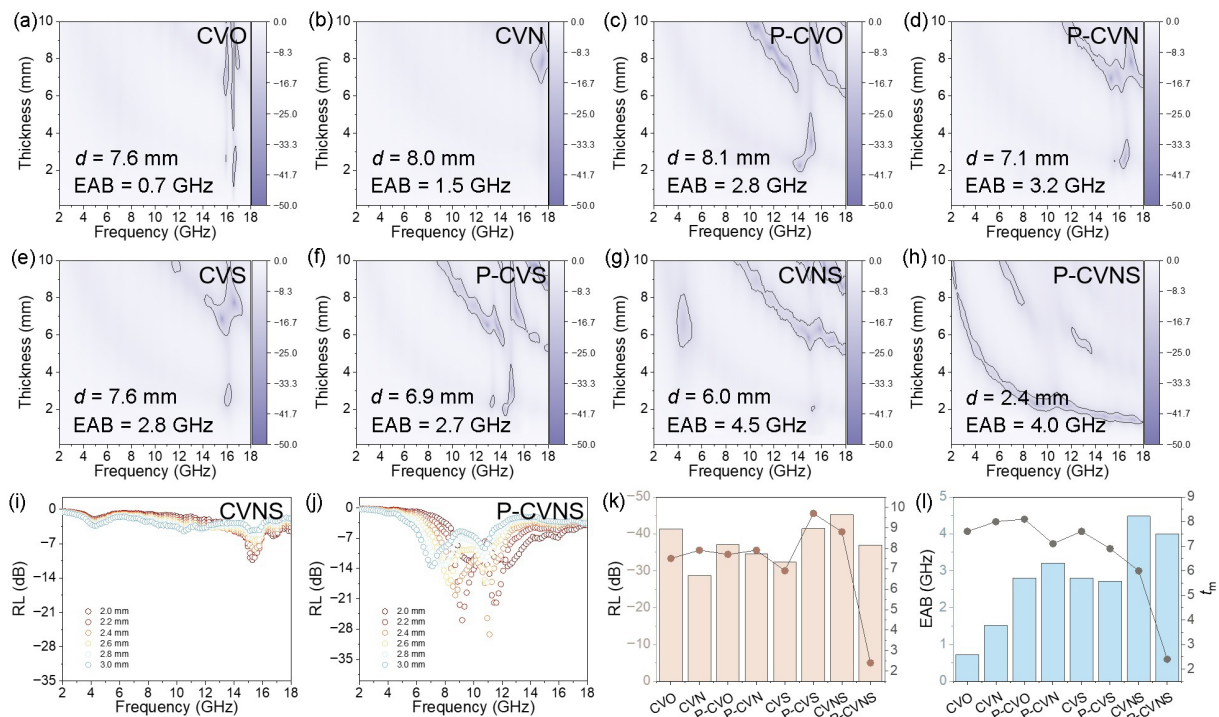


Figure 3 (a)–(h) EMW absorption characteristics of the samples. (i) and (j) The reflection loss of CVNS and P-CVNS at low thicknesses. (k) and (l) Performance comparison chart of the samples.

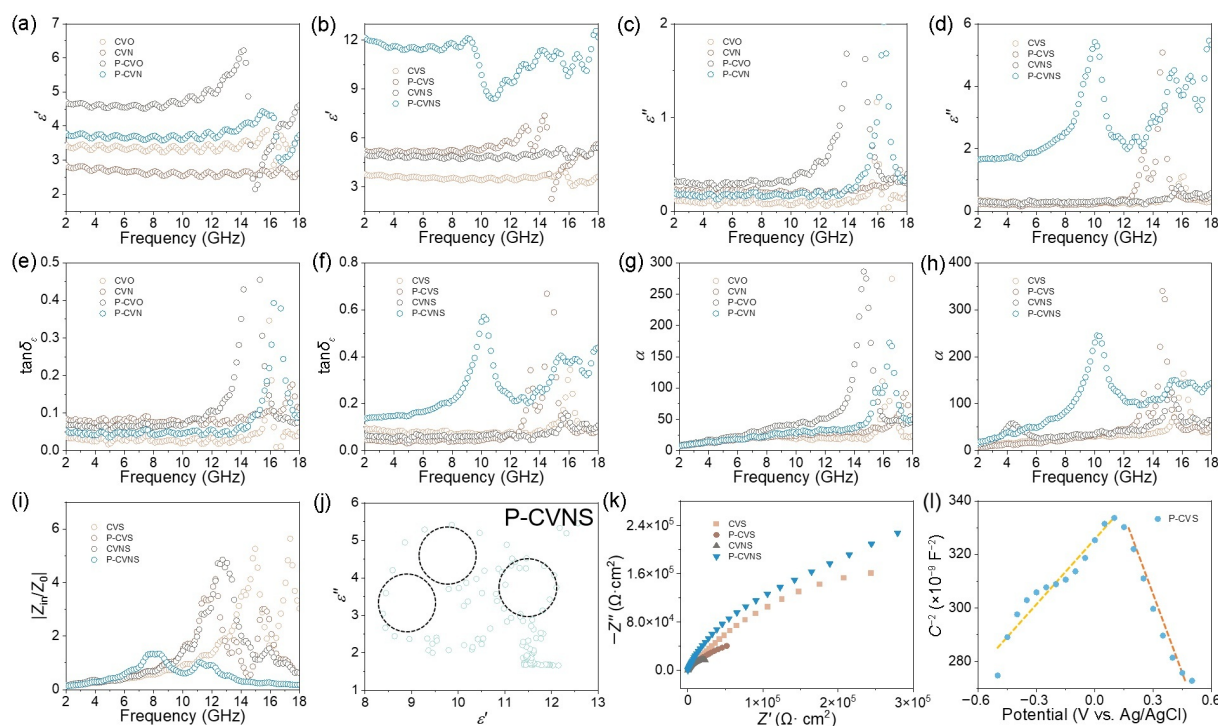


Figure 4 (a)–(d) Dielectric parameters of the samples. (e) and (f) Dielectric loss tangent image of the sample. (g) and (h) Attenuation constant image of the sample. (i) Impedance matching image of the sample and (j) Cole–Cole diagram of P-CVNS. (k) Nyquist plot of the sample. (l) Mott–Schottky plot of P-CVNS.

fluctuations in the permittivity spectra. Analysis of the dielectric loss tangent ($\tan\delta$) reveals that P-CVNS possesses higher loss values, signifying robust polarization relaxation loss (Figs. 4(e) and 4(f) [37]. This can be attributed to the heteroatom-regulated interfacial charge-polarization coupling effect. The introduction of P atoms induces charge redistribution at Co–N, Co–S, and vanadium-based heterointerfaces, resulting in the formation of localized polarization dipoles and internal electric fields. These features act as effective polarization centers under alternating electromagnetic fields, thereby triggering multiple Debye relaxation processes. Simultaneously, multiple heterointerfaces constructed via phase engineering provide abundant pathways for charge hopping and interfacial polarization, further bolstering the dielectric loss. The attenuation constant (α) was calculated according to the following Eq. (3) [38–40]

$$\alpha = \frac{\sqrt{2\pi f}}{c} \times \sqrt{(\mu''\epsilon'' - \mu'\epsilon') + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\mu'\epsilon'' + \mu''\epsilon')^2}} \quad (3)$$

As shown in Figs. 4(g) and 4(h), the P-CVNS sample exhibits the highest attenuation constant over the measured frequency range, indicating its superior EMW attenuation capability. This behavior can be attributed to the synergistic effect of P doping and multiphase heterostructures. The introduction of P modulates the dielectric response by optimizing carrier transport, while simultaneously introducing additional defect and interfacial polarization centers through lattice distortion and heterogeneous interfaces. Consequently, conduction loss and polarization loss are well balanced. This optimized dielectric response endows P-CVNS with favorable impedance matching, effectively facilitating the entry of incident EMWs into the absorber (Fig. 4(i) and Fig. S9 in the ESM). To further elucidate the dielectric polarization relaxation behavior and interfacial charge transport characteristics, Cole–Cole

plots were analyzed [41]. The dielectric loss behavior was investigated using the Debye theory with the following equations (Eqs. (4) and (5)) [42, 43]

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + (2\pi f\tau)^2} \quad (4)$$

$$\epsilon'' = \epsilon_{\infty} + \frac{2\pi f\tau(\epsilon_s - \epsilon_{\infty})}{1 + (2\pi f\tau)^2} \quad (5)$$

$$(\epsilon' - \epsilon_{\infty})^2 + (\epsilon'')^2 = (\epsilon_s - \epsilon_{\infty})^2 \quad (6)$$

As shown in Fig. 4(j) and Fig. S10 in the ESM, the P-CVNS sample displays multiple overlapping semicircles, indicating the presence of multiple dielectric relaxation processes. This suggests that the multiphase heterointerfaces, combined with P doping, collectively activate multi-scale polarization responses, thereby enhancing electromagnetic energy dissipation.

Electrochemical characterization was employed to elucidate the heteroatom-regulated interfacial electronic behavior in the multiphase heterostructure. The charge transport characteristics were further elucidated through the analysis of electrochemical impedance spectroscopy (EIS, Z' – Z'') (Fig. 4(k) and Fig. S11 in the ESM) [44–46]. Compared with other samples, the P-CVNS sample displays a larger arc radius and a steeper slope in the low-frequency region, signifying enhanced interfacial polarization effects. The heteroatom-doped samples exhibit stable and elevated open-circuit potential (OCP) values, indicating altered interfacial electronic states and charge distribution (Fig. S12 in the ESM) [47–50]. Furthermore, the phosphidated heterostructures show reduced corrosion current densities, reflecting increased charge transfer resistance and modulated Faradaic polarization (Fig. S13 in the ESM). These results confirm that heteroatom engineering can tailor

interfacial charge and polarization behavior, thereby contributing to optimized impedance matching and dielectric relaxation for high-performance EMW absorption. Mott-Schottky (M-S) plots were further analyzed, revealing that the P-CVNS sample exhibits both n-type and p-type semiconducting behaviors (Fig. 4(l) and Fig. S14 in the ESM) [51, 52]. The synergistic effect of the multiphase heterostructure and P-induced electronic modulation provides multiple relaxation pathways and promotes optimized charge transport, ultimately leading to outstanding EMW absorption performance.

To elucidate the mechanism by which P doping enhances EMW attenuation, DFT calculations were performed on the P-CVNS heterostructure [53, 54]. The charge density difference maps reveal distinct regions of electron accumulation and depletion at the heterointerfaces, demonstrating a pronounced redistribution of interfacial electrons following heteroatom doping (Fig. 5(a) and Fig. S15 in the ESM). This asymmetric charge transfer behavior confirms the establishment of strong electronic coupling among the Co_2N , Co_3S_4 , VN, and VS phases. Notably, the P doping enhances the interfacial polarization, creating a multitude of localized dipole centers and built-in electric fields. Density of states (DOS) analysis further indicates that, compared to the individual components, the heterostructure exhibits a higher DOS near the Fermi level, suggesting improved electronic conductivity and facilitated interfacial charge transfer (Fig. 5(b)). The coexistence of metallic and semiconducting characteristics across different phases

establishes multiple electron migration pathways, thereby facilitating charge migration across the heterointerfaces. Analysis of the energy band structure reveals that these four phases exhibit distinct energy band distributions near the Fermi level (Figs. 5(c)–5(f)). Among them, Co_2N and VN possess relatively high electronic conductivity due to their continuous electronic bands near the Fermi level. Conversely, Co_3S_4 and VS exhibit additional semiconducting features. The coexistence of multiple phases creates an interfacial energy level gradient, which facilitates electron migration and enhances polarization relaxation processes. Electron localization function (ELF) maps reveal heterogeneous charge distributions and localized electron localization regions (Figs. 5(g)–5(j)) [55–57]. Pronounced electron localization is observed around specific atomic sites, indicating the formation of localized electronic states induced by P doping and multiphase interactions [58–60]. Consequently, these results demonstrate that P doping plays a pivotal role in reconstructing the interfacial electronic structure of the $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ heterostructure. The heteroatom-induced charge redistribution and abundant polarization centers synergistically enhance interfacial polarization and dielectric relaxation, thereby promoting electromagnetic energy dissipation.

The three-dimensional radar cross-section (RCS) simulations were conducted using a perfect electric conductor (PEC) substrate with dimensions of $150\text{ mm} \times 150\text{ mm} \times 1\text{ mm}$ coated with an absorbing layer of 3 mm thickness. The simulation results show

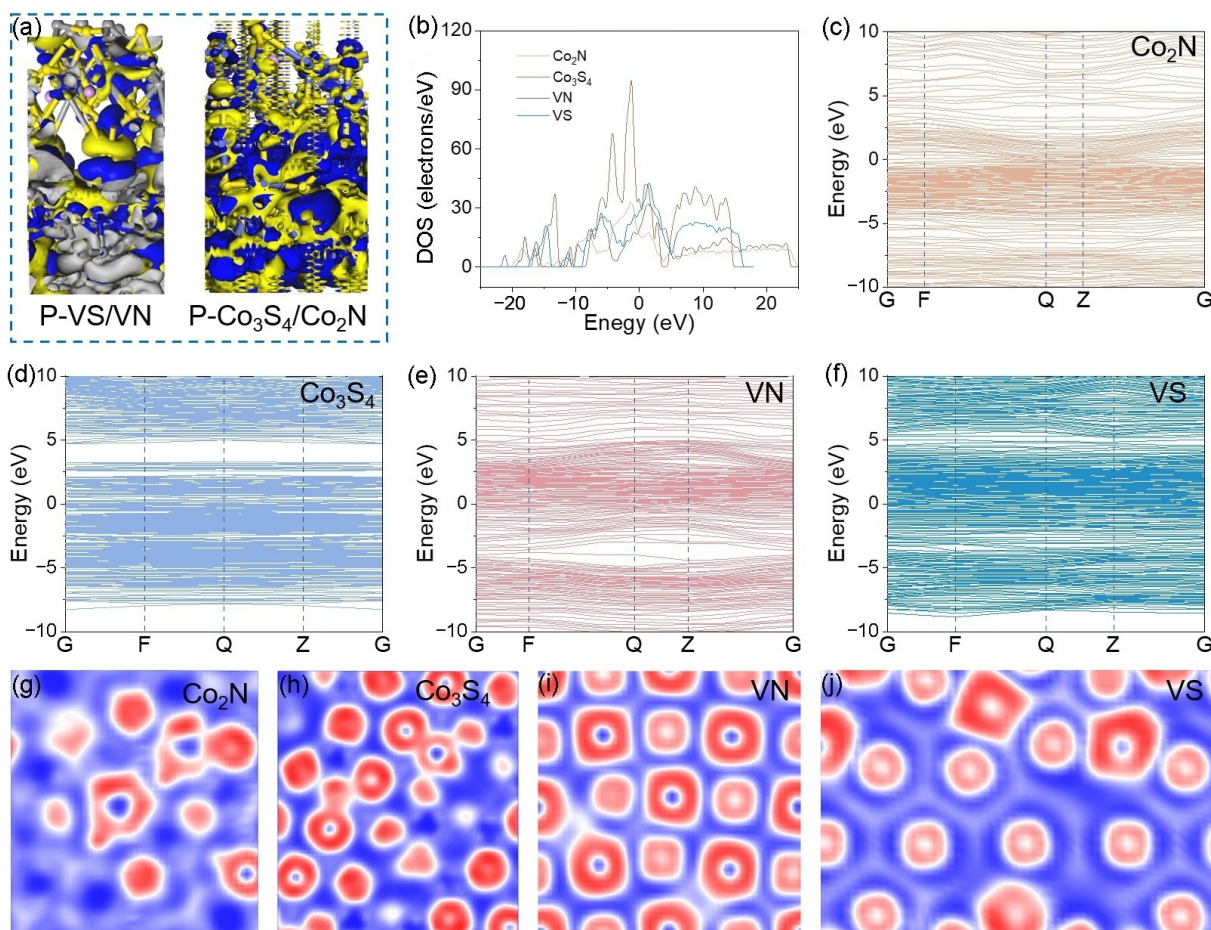


Figure 5 (a) The differential charge density image of P-VS/VN and P- $\text{Co}_3\text{S}_4/\text{Co}_2\text{N}$. (b) DOS plots, (c)–(f) band structure plots, and (g)–(j) ELF plots for Co_2N , Co_3S_4 , VN, and VS.

that, compared with the bare PEC, the scattering intensity of the surface covered by the absorbing coating is significantly reduced (Fig. 6(a) and Fig. S16 in the ESM), demonstrating the excellent EMW suppression capability of the P-CVNS coating [61–66]. This indicates that EMW reflection is effectively suppressed, and the incident energy can be more smoothly coupled into the interior of the material. The P-CVNS consistently exhibits the lowest RCS values across the entire observation angle range, demonstrating its excellent impedance matching and EMW attenuation capabilities (Figs. 6(b) and 6(c)). Figures 6(d)–6(g) further elucidate the electromagnetic energy conversion process. Incident EMWs are progressively converted into thermal energy within the multiphase heterostructures through interfacial charge migration, polarization relaxation, and conduction loss. The $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ heterointerface network enhances electromagnetic fields, induces charge accumulation, and promotes efficient electromagnetic energy dissipation. P doping reconstructs the electronic structure, promoting interfacial charge transfer and built-in electric fields, thereby enhancing polarization loss and EMW attenuation.

The outstanding EMW absorption performance of the P-doped multiphase heterostructure (P-CVNS) originates from the synergistic regulation of interfacial charge transfer and polarization behavior [67–70]. First, the incorporation of P atoms alters the local electronic environment. Owing to the moderate electronegativity and flexible bonding characteristics of P, its introduction into the $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ system leads to significant charge redistribution across different phases (Fig. 6(h)). This process generates asymmetric charge regions and localized dipoles at the heterointerfaces, thereby creating built-in electric fields [71–75]. Under alternating electromagnetic fields, these dipoles undergo polarization relaxation, generating enhanced dipole polarization loss. Second, the phase-engineered multicomponent architecture

provides abundant heterointerfaces, where charge carriers accumulate due to the mismatch in conductivity and permittivity, resulting in robust interfacial polarization [76–80]. Furthermore, the optimized electronic structure enables efficient and controllable charge transport, thereby enhancing conduction loss. Simultaneously, P doping regulates electron migration and suppresses excessive conductivity, thus maintaining favorable impedance matching. The synergy among interfacial polarization, dipole relaxation, conduction loss, and multiple scattering constructs a high-efficiency network for electromagnetic energy attenuation (Fig. 6(i)). In summary, regulating interfacial electronic structures via heteroatom engineering represents an effective strategy for achieving high-performance EMW absorption.

4 Conclusions

In summary, by means of a heteroatom doping strategy, we have successfully constructed a multiphase heterostructure of $\text{Co}_2\text{N}/\text{Co}_3\text{S}_4/\text{VN}/\text{VS}$ that exhibits high-performance EMW absorption. P doping effectively modulates the interfacial dielectric response, promotes charge redistribution, and creates abundant polarization centers. Meanwhile, the optimized carrier transport behavior achieves a favorable balance between dielectric loss and impedance matching, thereby facilitating the efficient dissipation of electromagnetic energy. The results demonstrate that the P-CVNS heterostructure possesses outstanding EMW attenuation capability. The heteroatom doping approach employed in this study provides an effective pathway for tuning interfacial polarization and charge transport in multiphase heterostructures, and is expected to be broadly applicable to other EMW absorbing materials featuring complex heterointerfaces.

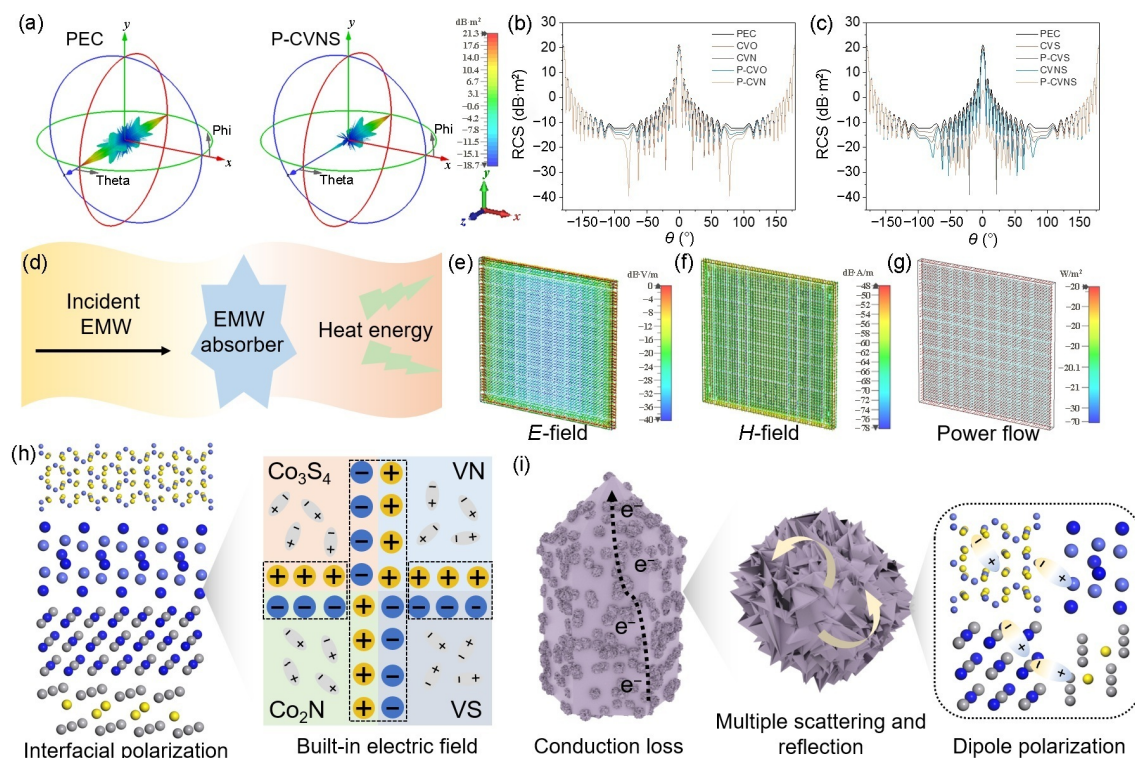


Figure 6 (a) 3D images of RCS attenuation for PEC and P-CVNS. (b) and (c) Images of RCS attenuation for the samples at different angles. (d) Schematic diagram of EMW energy conversion. (e)–(g) E-field, H-field, and power flow diagram. (h) and (i) Diagram illustrating the EMW attenuation mechanism of the P-CVNS sample.

Electronic Supplementary Material: Supplementary material (XPS spectra, Raman spectra, TEM images, SAED characterizations, electromagnetic wave absorption performance, electrochemical measurements, differential charge density simulation, and RCS attenuation simulation results) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909137>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

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

Author contribution statement

W. C. Z.: Writing – original draft. Y. L.: Validation, methodology, data curation. D. L.: Validation, formal analysis. Z. Q. G. and G. L. W.: Writing – review & editing. All the authors have approved the final manuscript.

Use of AI statement

None.

References

- [1] Yu, K. L.; Pan, Y. L.; Zhang, Z. L.; Xiang, H. Y.; Zeng, H. B.; Chen, Z. S. Recent progress in low-dimensional transition metal dichalcogenides materials for electromagnetic wave absorption. *Chem. Eng. J.* **2025**, *512*, 162622.
- [2] Huang, M. Q.; Wang, L.; Pei, K.; Li, B. X.; You, W. B.; Yang, L. T.; Zhou, G.; Zhang, J. C.; Liang, C. Y.; Che, R. C. Heterogeneous interface engineering of bi-metal MOFs-derived $\text{ZnFe}_2\text{O}_4\text{-ZnO-Fe@C}$ microspheres via confined growth strategy toward superior electromagnetic wave absorption. *Adv. Funct. Mater.* **2024**, *34*, 2308898.
- [3] Wen, L. C.; Cheng, S. Y.; Shang, H. C.; Sheng, D. H.; Li, W. J.; Qi, X. S.; Xie, A. M. Regulating interfacial strain from tensile to compressive state in transition-metal-sulfides/carbon for high-performance electromagnetic wave absorption. *Adv. Funct. Mater.* **2026**, *36*, e74621.
- [4] Sheng, D. H.; Cheng, S. Y.; Zhang, M. M.; Zhang, J. L.; Zhu, X. F.; Li, W. J.; Zhang, B.; Xie, A. M. Nanocurvature-activated dipolar polarization in M-N₄ single-atom sites for high-performance electromagnetic wave absorption. *Adv. Sci.* **2026**, *13*, e75115.
- [5] Cheng, S. Y.; Chen, Z. L.; Sheng, D. H.; Dong, W.; Cao, R.; Su, Z. B.; Wu, M. D.; Zhu, X. F.; Xie, A. M.; Mukherjee, S. et al. Sustainable electromagnetic interference shielding materials from cellulose-grafted n-type polymers. *Nat. Commun.* **2025**, *16*, 8608.
- [6] Yan, Y. F.; Lun, A. G.; Gao, B. S.; Liu, Y. H.; Jia, D. C.; Zhou, Y.; Huang, X. X. Advances in TMDs-based electromagnetic wave absorbers: From structural engineering to multicomponent synergy. *Nanomicro Lett.* **2027**, *19*, 21.
- [7] Gao, B. S.; Yan, Y. F.; Zhang, K. L.; Liu, D. D.; Huang, X. X. Ultralight broadband electromagnetic wave absorption enabled by interface-engineered two-layered periodic carbon fiber fabrics. *Adv. Funct. Mater.* **2026**, *36*, e32108.
- [8] Yan, Y. F.; Cheng, Z. Y.; Chen, T.; Zhou, E.; Gao, B. S.; Qin, G. Y.; Ma, G. S.; Huang, X. X. Rational high-entropy doping strategy via modular *in situ*/post solvothermal doping integration for microwave absorption. *J. Adv. Ceram.* **2025**, *14*, 9221168.
- [9] Zhang, S. J.; Zheng, J. J.; Liang, X. W.; Lan, D.; Niu, L. Y.; Zhao, X. M.; Zhao, Z. W.; Zhang, S. Y.; Wu, G. L.; Li, X. C. Phosphorus-driven heteroatom doping in mesoporous carbon hollow platelets enables efficient electromagnetic wave absorption. *Small* **2025**, *21*, e09237.
- [10] Tao, J. Q.; Yan, Y.; Zhou, J. T.; Wang, J.; Chen, P.; Tan, R. Y.; Xu, L. L.; Zhu, H. B.; Zhu, W. H.; Huang, H. X. et al. Anionic high-entropy doping engineering for electromagnetic wave absorption. *Nat. Commun.* **2025**, *16*, 3163.
- [11] Guo, Z. Y.; Qin, L. Y.; Fu, L. Y.; Liu, R. B.; Zhou, J. D. Transition-metal doping induced electronic structure modulation of FeTe for enhanced electromagnetic wave absorption. *Nano Energy* **2026**, *151*, 111808.
- [12] Xie, P. T.; Wu, H. K.; Cheng, Z. X.; Liu, M. X.; Liu, Y.; Pang, W. K.; Fan, R. H.; Liu, Y. Ultralow-frequency epsilon-near-zero states in 3D-printed high-entropy alloy metacomposites for ultra-thin perfect RF absorption. *Adv. Mater.* **2026**, *38*, e16951.
- [13] Zhou, L.; Yin, Y. R.; Nematov, D.; Dai, H. L.; Gu, Y. Y.; Yu, S. F.; Bi, L. A high-performance cobalt-free cathode for proton-conducting solid oxide fuel cells via multi-element doping in $\text{Sr}_2\text{Fe}_2\text{O}_6$. *Sustainable Mater. Technol.* **2026**, *48*, e01936.
- [14] Zhang, K.; Zhang, J. L.; Dang, L.; Wu, Y. H.; He, M. K.; Guo, H.; Shi, X. T.; Qiu, H.; Gu, J. W. High intrinsic thermal conductivity and low dielectric constant of liquid crystalline epoxy resins with fluorine-containing semi-IPN structures. *Sci. China Chem.* **2025**, *68*, 2615–2627.
- [15] Yan, Y. F.; Qin, G. Y.; Zhang, K. L.; Gao, B. S.; Ma, G. S.; Huang, X. X.; Zhou, Y. Enhancing microwave absorption performance of MoS_2 by synergistic effect of Fe doping. *J. Adv. Ceram.* **2025**, *14*, 9221039.
- [16] Hou, H. Y.; Ma, D. W.; Zhang, Z. N.; Jia, Z. R. Synergistic mechanism and performance optimization of dielectric-magnetic composite absorbing material. *Acta Phys. Chim. Sin.* **2026**, *42*, 100325.
- [17] Guo, Z. Q.; Jia, Z. R.; Lan, D.; Shan, P. X.; Zhang, Z. Y.; Gao, Z. G.; Wu, G. L. Synergistic polarization relaxation loss in multimetallic hierarchical hybridization and preferred orientation strategies for electromagnetic wave absorption. *Adv. Funct. Mater.*, in press, DOI: 10.1002/adfm.77757.
- [18] Liu, X. D.; Zhang, S.; Yu, M.; Zhao, X. X.; Jia, Y. W.; Huang, Y.; Zong, M. WS_2 nanosheets anchored on N-doped carbon fibers for superior electromagnetic wave absorption. *Chem. Eng. J.* **2023**, *465*, 142932.
- [19] Wang, R.; Zhang, R.; Yan, Y. X.; Li, G. Y.; Li, Y.; Wang, F. J.; Wu, Y. Z.; Ran, F. Controllable synthesis and “fast-charging” mechanism of hollow-micropencil $\text{Co}_3\text{V}_2\text{O}_8$ from perspective of ion diffusion in crystal structure. *Adv. Funct. Mater.* **2025**, *35*, 2422111.
- [20] Pan, Y. L.; Wang, X. B.; Yu, K. L.; Jin, M. L.; Wang, X.; Li, G. R.; Zhang, Z. L.; Chen, Z. S. Porous heterojunction-engineered carbon fibers for ultra-broadband electromagnetic wave absorption. *Carbon* **2026**, *253*, 121430.
- [21] Hou, X.; Feng, X. R.; Jiang, K.; Zheng, Y. C.; Liu, J. T.; Wang, M. Recent progress in smart electromagnetic interference shielding materials. *J. Mater. Sci. Technol.* **2024**, *186*, 256–271.
- [22] Liang, Z. J.; Shen, D.; Wei, Y.; Sun, F. F.; Xie, Y.; Wang, L.; Fu, H. G. Modulating the electronic structure of cobalt-vanadium bimetal catalysts for high-stable anion exchange membrane water electrolyzer.

- Adv. Mater.* **2024**, *36*, 2408634.
- [23] Xu, J.; Shu, R. W.; Wan, Z. L.; Shi, J. J. Construction of three-dimensional hierarchical porous nitrogen-doped reduced graphene oxide/hollow cobalt ferrite composite aerogels toward highly efficient electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2023**, *132*, 193–200.
- [24] Ma, G. S.; Li, J.; Yan, Y. F.; Qin, G. Y.; Gao, B. S.; Chen, T.; Cheng, Z. Y.; Huang, X. X. Carbon-transition metal dichalcogenide composites: A comprehensive review on electromagnetic wave absorption. *Carbon* **2025**, *244*, 120690.
- [25] Wu, G. R.; Zhu, J. H.; Guo, X. M.; Zhang, C. M.; He, M. T.; Qiu, H.; Ma, D. W. Construction of schottky barrier and the enhanced interface polarization effect of C@ZnO/Sn@GaN for high performance electromagnetic wave absorption. *Acta Phys. Chim. Sin.* **2026**, *42*, 100324.
- [26] Wei, Q.; Qiu, Y. R.; Yang, T. F.; Jiang, Y. L.; Zhu, S. H.; Zhou, J.; Liu, C. C.; Hou, W. J.; Wang, Y.; Liu, D. Synergistic engineering of heterointerfaces in Metal@Carbon nanosheets for bifunctional electromagnetic wave absorption and electrochemical energy storage. *Acta Phys. Chim. Sin.* **2026**, *42*, 100320.
- [27] Raja, D. S.; Cheng, P. Y.; Cheng, C. C.; Chang, S. Q.; Huang, C. L.; Lu, S. Y. *In-situ* grown metal-organic framework-derived carbon-coated Fe-doped cobalt oxide nanocomposite on fluorine-doped tin oxide glass for acidic oxygen evolution reaction. *Appl. Catal. B Environ.* **2022**, *303*, 120899.
- [28] Huang, X. G.; Cong, W. J.; Chen, Y.; Quan, B. Conductive network reconstruction driven by carbonization: Enabling the transition of hard carbon from electromagnetic wave absorption to shielding. *Carbon* **2026**, *251*, 121326.
- [29] Xu, S.; Jia, Z. R.; Lan, D.; Shi, M. J.; Gao, Z. G.; Wu, G. L. Synergistic modulation ion regulation and lattice distortion tailoring built-in electric fields for electromagnetic wave absorption. *Adv. Funct. Mater.* **2026**, *36*, e76265.
- [30] Hu, Y. P.; Dong, S. J.; Zhou, T.; Ma, D. W.; Zhang, D. H.; Xia, H. S.; Si, Y. J.; Song, A. M.; Xu, G. M. MoS₂-modulated TiO₂/C hydrangea structures for electromagnetic wave absorption via dielectric loss dominances. *Acta Phys. Chim. Sin.*, in press, DOI: 10.1016/j.actphy.2026.100345.
- [31] Huang, X. G.; Guan, J. P.; Feng, Y. J.; Zhang, Q. H.; Quan, B.; Shao, G. F.; Gu, L.; Guo, T. C.; Sun, G. M.; Zhu, X. H. Mn and O defect modulation in birnessite creates multiplicate polyhedra to improve dielectric and magnetic losses. *Cell Rep. Phys. Sci.* **2025**, *6*, 102350.
- [32] Huang, W. H.; Chen, J. M.; Gao, W. M.; Wang, L.; Li, P. B.; Zhang, Y. N.; Yin, Z.; Yang, Y. H. “Host-guest” crystalline Mo/Co-framework induced phase-conversion of MoC_x in carbon hybrids for regulating absorption of electromagnetic wave. *Carbon* **2022**, *197*, 129–140.
- [33] Xu, S.; Jia, Z. R.; Lan, D.; Shi, M. J.; Gao, Z. G.; Wu, G. L. Synergistic polarization relaxation in multi-level hybridization and preferred orientation strategies for electromagnetic wave absorption. *Adv. Funct. Mater.* **2026**, *36*, e75567.
- [34] Gao, Y. T.; Fan, C. M.; Lan, D.; Chen, J.; Liu, L. X.; He, Q. C.; Wang, Y. Q. Constructing a hierarchical micronetwork structure for Mo₂C/SiC composite thin films to achieve flexibility and efficient absorption of electromagnetic waves. *Int. J. Miner. Metall. Mater.*, in press, DOI: 10.1007/s12613-026-3517-3.
- [35] Yang, S. H.; Guo, Z. Q.; Jia, Z. R.; Liu, Y.; Wang, D. S.; Li, Z. C.; Li, H. F.; Qiu, H.; Wu, G. L. Precisely engineered heterointerfaces in bimetallic MOFs enable multiscale polarization synergy for efficient electromagnetic attenuation. *Acta Phys. Chim. Sin.* **2026**, *42*, 100348.
- [36] Yu, G. Y.; Shao, G. F.; Xu, Z. L.; Chen, Y.; Huang, X. G. Hierarchical interface-engineered magnetic graphene-SiCN aerogels via a stepwise confinement strategy for low-frequency and broadband microwave absorption. *J. Adv. Ceram.* **2025**, *14*, 9221187.
- [37] Tian, Z. N.; Liu, J. Y.; Zhang, M.; Jia, Q. Q.; Liu, M. B.; Li, Z. J.; Wang, T.; Zhao, W. J.; Ma, D. W.; Qi, X. L. Constructing selenium-vacancy-rich SiC@CoSe_x nanocomposites to boost dipole and interfacial polarization for electromagnetic wave absorption. *Acta Phys. Chim. Sin.* **2026**, *42*, 100323.
- [38] Dong, Y. H.; Wu, G. R.; Gao, Z. G.; Lan, D.; Qiu, H.; Jia, Z. R.; Wu, G. L. Simultaneous modulation of vacancy and heterointerface of double-matrix phosphorus doped NiSe₂/CoSe₂ composite for “dual-core-driven” electromagnetic wave absorption. *Nano Res.*, in press, DOI: 10.26599/NR.2026.94908868.
- [39] Zhang, X.; Wang, H. Y.; Hao, Y. L.; Qu, Y. P.; Wang, X. H.; Jiang, W. Y.; Li, H. F.; Deng, C. Y.; Qi, X. S. Peanut biomimetic functional phases-engineered metacomposites with loading-insensitive epsilon-negative response for electromagnetic shielding. *Acta Phys. Chim. Sin.* **2026**, *42*, 100326.
- [40] Zhang, Y. L.; Ruan, K. P.; Zhou, K.; Gu, J. W. Controlled distributed Ti₃C₂T_x hollow microspheres on thermally conductive polyimide composite films for excellent electromagnetic interference shielding. *Adv. Mater.* **2023**, *35*, 2211642.
- [41] Wang, W.; Jia, Z. R.; Liu, Y.; Xu, X. Y.; Lan, D.; Gao, Z. G.; Wu, G. L. Lightweight broadband transition-metal microwave absorbers synergistic engineering of multi-interfacial polarization and hollow conductive networks. *J. Mater. Sci. Technol.* **2027**, *285*, 132–141.
- [42] Liu, X. Y.; Zhao, Y.; Zhang, Y. L.; Cui, X. C.; Xue, Y.; Lu, X. Y.; Gu, J. W. Bioinspired layered-gradient nanocomposites for intelligent electromagnetic skins with GHz-THz wave absorption, shielding, and solvent-driven actuation. *Nanomicro Lett.* **2026**, *18*, 344.
- [43] Dong, Y. H.; Lan, D.; Xu, S.; Gu, J. W.; Jia, Z. R.; Wu, G. L. Controllable fiberization engineering of cobalt anchored mesoporous hollow carbon spheres for positive feedback to electromagnetic wave absorption. *Carbon* **2024**, *228*, 119339.
- [44] Xu, H. Y.; Liu, M. J.; Huang, L. T.; Zhang, X.; Ma, Z.; Zhu, C. L.; Cao, F. H.; Chen, Y. J. Enhanced dielectric loss via six-coordinated Er single atoms on porous carbon nanofibers for high-performance electromagnetic wave absorption. *Adv. Funct. Mater.* **2025**, *35*, 2502952.
- [45] Yuan, M. Y.; Zhao, B.; Yang, C. D.; Pei, K.; Wang, L. Y.; Zhang, R. X.; You, W. B.; Liu, X. H.; Zhang, X. F.; Che, R. C. Remarkable magnetic exchange coupling via constructing bi-magnetic interface for broadband lower-frequency microwave absorption. *Adv. Funct. Mater.* **2022**, *32*, 2203161.
- [46] Yan, J.; Zhang, Z. N.; Ma, D. W.; Zhang, X. Y.; Ye, Z. D.; Chen, X. F. Melamine-assisted topotactic transformation of MOFs into needle-like α -MoC/ β -Mo₂C for high-performance electromagnetic wave absorption and corrosion resistance. *Acta Phys. Chim. Sin.* **2026**, *42*, 100328.
- [47] Tao, J. Q.; Sugumaran, P. J.; Zhao, Y. J.; Wang, C. J.; Jamwal, U.; Liu, Y. J.; Duan, L. T.; Chu, W. M.; Ang, C. K.; Ding, J. et al. Cascaded built-in electric fields engineering for electromagnetic wave absorption. *Adv. Mater.* **2026**, *38*, e23404.
- [48] Zhang, Y. C.; Ma, D. C.; Zhang, X. Z.; Zhu, C. L.; Gao, S. T. Co_{0.5}Zn_{0.5}Fe₂O₄ modified residual carbon as an excellent microwave absorber. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 534–545.
- [49] Wang, J.; Wang, Y. B.; Wu, J. R.; Wang, D. S.; Liu, C.; Huang, H. M.; Wang, Y. Y.; Zhang, C. K. Synergizing magnetic exchange resonance and hierarchical dielectric relaxation in multiphase core-shell heterojunctions for efficient microwave dissipation. *Acta Phys. Chim. Sin.* **2026**, *42*, 100336.
- [50] Lian, Y. Y.; Dong, Q. Z.; Wang, D. S.; Wang, L.; Liu, S. S.; Jiang, Y.; Wu, N. N. NIR-triggered photothermal antibacterial melamine foam decorated by MXene/Ag NWs with integrated electromagnetic interference shielding for potential biofilm-infection management. *Acta Phys. Chim. Sin.*, in press, DOI: 10.1016/j.actphy.2026.100352.
- [51] Zhong, X.; He, M. K.; Zhang, C. Y.; Guo, Y. Q.; Hu, J. W.; Gu, J. W. Heterostructured BN@Co-C@C endowing polyester composites excellent thermal conductivity and microwave absorption at C band. *Adv. Funct. Mater.* **2024**, *34*, 2313544.
- [52] Zhang, Y. C.; Gao, S. T.; Zhang, X. Z.; Ma, D. C.; Zhu, C. L.; He, J. Structural and microwave absorption properties of CoFe₂O₄/residual carbon composites. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 221–232.
- [53] Liu, X. N.; Lei, Z.; Lu, M. X.; Ma, D. W.; Wang, C.; Wu, Z. H.; Zhang, D. H. Construction of Fe₃O₄@ZIF-67 based flexible

- multifunctional hydrogels for electromagnetic interference shielding and strain sensing. *Acta Phys. Chim. Sin.* **2026**, *42*, 100354.
- [54] Cai, Y. S.; Jia, Z. R.; Wu, Z. H.; Zhou, W. C.; Xu, X. Y.; Wang, Y.; Gao, Z. G.; Qiu, H.; Wu, G. L. Selenium nano cluster-modified ZnS/Co₃S₂@C heterogeneous interface for excellent electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2027**, *277*, 66–75.
- [55] Niu, Z. P.; Wang, Y.; Tian, Q. F.; Wang, J.; Gao, Z. G.; Lan, D.; Wu, G. L. Hierarchical aggregation structure regulation and electromagnetic loss mechanism of cross-linked polyaniline in polymer wave absorbers. *Carbon* **2025**, *233*, 119848.
- [56] Xue, R.; Lan, D.; Qiang, R.; Zang, Z. C.; Ren, J. W.; Shao, Y. L.; Rong, L.; Gu, J. W.; Fang, J. B.; Wu, G. L. Synergistic dielectric regulation strategy of one-dimensional MoO₃/Mo₂C/C heterogeneous nanowires for electromagnetic wave absorption. *Carbon* **2025**, *233*, 119877.
- [57] Song, S. X.; Zheng, B. Y.; Chen, L. H.; Shu, H. M.; Gao, D. T.; Lan, D.; Li, T. X.; Liu, X.; Ma, Y. Fabrication of ZnCoM (M = Al, Ni, Fe) layered double hydroxide materials for high-performance asymmetric supercapacitors. *J. Energy Storage* **2025**, *134*, 118282.
- [58] Tariq, M. R.; Ahmad, M.; Naik, M. U. D.; Khan, I.; Zhang, B. L. A comprehensive review of the advancement of transition metal oxide nanocomposites for microwave absorption. *Coord. Chem. Rev.* **2025**, *533*, 216535.
- [59] Huo, Y. Y.; Wang, Z. Y.; Zhang, Y. L.; Wang, Y. Z. High-entropy ferrite with tunable magnetic properties for excellent microwave absorption. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 668–677.
- [60] Zhang, Y. Y.; Lan, D.; Wang, Z. H.; Xu, G. D.; Gao, Z. H.; Bu, G. X.; Zhong, X. Z.; Yin, P. F. Modulation of magnetodielectric equilibrium in porous biochar embedded with MOF-derived CeO₂/Fe₃O₄ for excellent electromagnetic absorption and anti-microbial properties. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 387.
- [61] Chen, X. L.; Lan, D.; Zhou, L. T.; Liu, H. L.; Song, X. Y.; Wang, S. Y.; Zou, Z. Y.; Wu, G. L. Review of recent advances in ferrite-based materials: From synthesis techniques to electromagnetic wave absorption performance. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 591–608.
- [62] Jiang, F. J.; Chu, G. Y.; Nie, Z. G.; Zhao, Z. Y.; Yang, X. N.; Wang, R.; Guo, X. L.; Chen, J. Q.; Jiang, M. Y.; Qi, S. H. et al. Multifunctional, sandwich-structured ANF/PEDOT:PSS/MXene film with efficient electromagnetic interference shielding and thermal management. *Colloids Surf. A* **2026**, *731*, 139053.
- [63] Wang, L.; Liu, J. R.; Xie, S. H.; Deng, Y. L.; Wang, Z.; Hou, S. Y.; Yue, S. Y.; Wang, G.; Wu, N.; Zeng, Z. H. La-substituted W-type barium-nickel ferrites for tunable and high-performance electromagnetic wave absorption. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 645–656.
- [64] Zheng, W.; Li, Y. R.; Zhang, A. B. The effect of surface roughness of magnetic particles on the electromagnetic wave absorbing performance of Fe₃O₄/multiwalled carbon nanotubes hybrids. *ChemistrySelect* **2022**, *7*, e202104115.
- [65] Yang, S. H.; Zhao, P. Y.; Lu, X. Y.; Hao, X. Y.; Wu, Y. F.; Wang, H. Y.; Zhou, T.; Wang, G. S. Synthesis and high frequency structure simulator electromagnetic simulation of hollow NC@CeO₂ nanospheres for broad absorption bandwidth. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 678–688.
- [66] Xiao, J. X.; Zhan, B. B.; He, M. K.; Qi, X. S.; Gong, X.; Yang, J. L.; Qu, Y. P.; Ding, J. F.; Zhong, W.; Gu, J. W. Interfacial polarization loss improvement induced by the hollow engineering of necklace-like PAN/carbon nanofibers for boosted microwave absorption. *Adv. Funct. Mater.* **2025**, *35*, 2316722.
- [67] Gu, Y. Y.; Shi, J.; Nematov, D.; Liu, A. Q.; Yin, Y. R.; Dai, H. L.; Bi, L. A brief review of high-entropy oxides in solid oxide fuel cell applications. *Mater. Sci. Eng. B* **2026**, *327*, 119260.
- [68] Yang, S.; Yin, Y. R.; Boulfrad, S.; Dai, H. L.; Yu, S. F.; Gu, Y. Y.; Bi, L. Synergistic doping in proton-conducting oxides unlocks high conductivity and low proton trapping. *Adv. Funct. Mater.* **2026**, *36*, e74539.
- [69] Liu, L. L.; Lin, M. M.; Wang, L. N.; Liu, Z.; Guan, L.; Li, Q. L.; Lu, H. X.; Wang, Z. Y.; Zhao, B.; Zhang, R. Adaptable liquid metal putty for high electromagnetic shielding. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 1987–1996.
- [70] Song, W. H.; Dong, X. C.; Yin, Y. R.; Yu, S. F.; Gu, Y. Y.; Bi, L. Reviving the activity of Si-contaminated cathodes via chloride anion doping for proton-conducting solid oxide fuel cells. *J. Adv. Ceram.* **2026**, *15*, 9221262.
- [71] Zhu, C. T.; Liu, P.; Chen, J.; Ding, Z. X.; Tang, G. H.; Gao, Q. Q.; Ni, Y. X.; Xu, K.; Hao, Z. L.; Xu, G. J. et al. Constructing Ti₃C₂T_x-MXene-based gradient woodpile structure by direct ink writing 3D printing for efficient microwave absorption. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 657–667.
- [72] Zhang, W. L.; Zhao, C.; Lan, D.; Xu, X. L.; Jia, Z. R.; Xu, X. Z. Enhanced interface polarization and optimized impedance matching in MoS₂/ZrO₂/Cf composite for microwave absorption. *Carbon* **2026**, *257*, 121698.
- [73] Shao, G. F.; Xu, R. P.; Chen, Y.; Yu, G. Y.; Wu, X. D.; Quan, B.; Shen, X. D.; Huang, X. G. Miniaturized hard carbon nanofiber aerogels: From multiscale electromagnetic response manipulation to integrated multifunctional absorbers. *Adv. Funct. Mater.* **2024**, *34*, 2408252.
- [74] Ban, Q. F.; Song, Y. J.; Li, L. W.; Zhang, H. L.; Wu, X. Y.; Liu, J.; Qin, Y. S.; Lan, D.; Zhang, T. T.; Kong, J. Confined diffusion engineering of FeCoNi-embedded hollow carbon microcage toward controllable electromagnetic wave absorption and anticorrosive polyvinylidene fluoride composite in marine environment. *Small* **2025**, *21*, e08008.
- [75] Wang, Y. T.; Han, H.; Bian, H. Y.; Li, Y. J.; Lou, Z. C. Multi-interface structure design of bamboo-based carbon/Co/CoO composite electromagnetic wave absorber based on biomimetic honeycomb-shaped superstructure. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 631–644.
- [76] Zhao, Z. H.; Kou, K. C.; Zhang, L. M.; Wu, H. J. High efficiency electromagnetic wave absorber derived from transition metal layered double hydroxides. *J. Colloid Interface Sci.* **2020**, *579*, 733–740.
- [77] Zhao, J.; Lai, H. R.; Li, M. Anchoring 1T-MoS₂ petals on N-doped reduced graphene oxide for exceptional electromagnetic wave absorption. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 619–630.
- [78] Zeng, B. L.; Zhang, F. R.; Zhao, K. H.; Ahmad, M.; Wu, J. F.; Zhang, L.; Lan, D.; Zhang, B. L. Multilayered heterostructures and multicomponent synergy in MnO@HsGDY@NC/Ni magnetic nanofibers for enhanced electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2026**, *251*, 193–202.
- [79] Xie, X. B.; Liu, R. L.; Chen, C.; Lan, D.; Chen, Z. L.; Du, W.; Wu, G. L. Phase changes and electromagnetic wave absorption performance of XZn₂C (X = Fe/Co/Cu) loaded on melamine sponge hollow carbon composites. *Int. J. Miner. Metall. Mater.* **2025**, *32*, 566–577.
- [80] Weng, Z. H.; Niu, R. F.; Liu, Y.; Lan, D.; Li, Z. C.; Jia, Z. R.; Wu, G. L. MOF ligand-directed heterointerface engineering for tuning electromagnetic loss mechanisms in Fe₃O₄/polymetallic spinel ferrite composites. *Carbon* **2026**, *260*, 121971.



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