

# Cobalt-doped silicon carbide/carbon aerogels via a polymer-derived strategy for ultraefficient microwave absorption

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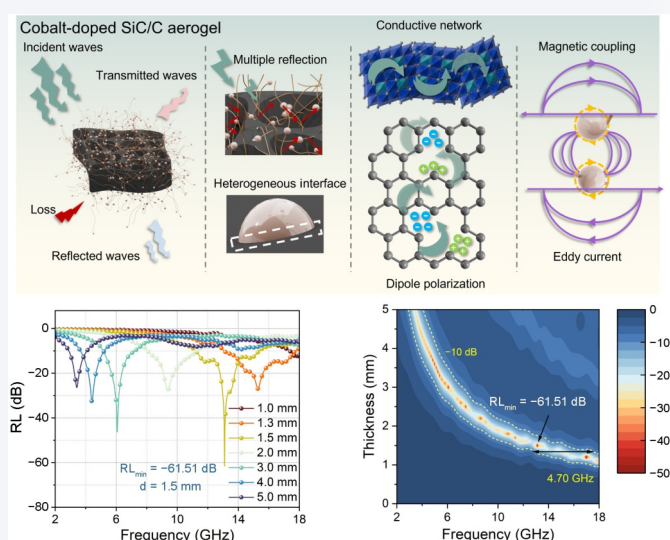
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**ABSTRACT:** Silicon carbide/carbon (SiC/C) composites have shown great promise as high-temperature electromagnetic wave absorbers, yet their practical application remains limited due to inherent impedance mismatch. In this study, a polymer-derived strategy for synthesizing three-dimensional porous Co-doped SiC/C aerogels using silicon-arylacetylene resin (PSA) as the precursor was reported. The precursor solution was prepared via a thiol-yne click reaction combined with coordination between Co ions and alkyne groups, which was subsequently processed through ambient-pressure gelation, freeze-drying, and pyrolysis to obtain the final aerogel. Co enhances electrical conductivity and optimizes dielectric loss through lattice doping into intrinsic silicon vacancies ( $V_{Si}$ ), while simultaneously introducing additional magnetic loss via metallic Co nanoparticles generated by carbothermal reduction. Furthermore, Co catalyzes the *in-situ* growth of worm-like SiC nanowires, constructing multiple heterogeneous interfaces. This integrated modulation strategy effectively improved impedance matching and established a synergistic dielectric-magnetic loss mechanism. The optimized aerogel exhibited outstanding microwave absorption performance, achieving a minimum reflection loss ( $RL_{min}$ ) of  $-61.51$  dB at  $13.10$  GHz and an effective absorption bandwidth (EAB) of  $4.70$  GHz at an ultrathin thickness of  $1.3$  mm. This work provides an innovative route for developing transition-metal-doped porous materials and offers an effective strategy for designing high-performance electromagnetic wave absorbers with tailored properties.

**KEYWORDS:** silicon carbide/carbon (SiC/C) aerogels, cobalt doping, polymer precursor, electromagnetic wave absorption, heterostructure



## 1 Introduction

The rapid advancement of aerospace, military stealth technologies, and electromagnetic protection has imposed higher requirements

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for efficient electromagnetic wave absorbing materials [1, 2]. Ideal absorbers must simultaneously meet core criteria of “strong, wide, thin, light” [3, 4]. Traditional magnetic loss materials (e.g., iron, cobalt, nickel, and their oxides) and dielectric loss materials (e.g., carbon-based materials), while exhibiting efficient wave absorption, suffer from inherent drawbacks such as high density, susceptibility to oxidation, or impedance mismatch, respectively [5–9]. Furthermore, their intrinsic thermal stability often falls short of the demands for service in extreme environments [10].

The integration of SiC, a wide bandgap semiconductor known for its excellent thermal stability and mechanical strength, into a

highly conductive carbon matrix enables the fabrication of SiC/C composites with distinctive electromagnetic properties [11–15]. The abundant SiC/C heterointerfaces constructed within such composites effectively stimulate interfacial polarization, thereby significantly enhancing the conversion and dissipation efficiency of electromagnetic energy [16]. By further designing controlled pore structures to process them into lightweight SiC/C aerogels, the porous structure not only facilitates deeper penetration of electromagnetic waves into the material but also extends their propagation path through scattering mechanisms, substantially improving energy attenuation efficiency [17, 18]. These characteristics make SiC/C aerogels a promising candidate for lightweight, broadband wave-absorbing applications in extreme environments. However, such materials lack an intrinsic magnetic loss mechanism, resulting in insufficient overall loss capability. This limits the tunable range of the absorption bandwidth, thereby constraining their practical effectiveness over broader frequency ranges.

In recent years, transition metal doping has attracted widespread attention because it can introduce additional magnetic loss mechanisms (e.g., natural resonance and eddy current loss) into the intrinsic dielectric loss system [19–22], while modulating the graphitization degree of the carbon matrix and interface characteristics to optimize dielectric behavior, reconstitute intrinsic electromagnetic parameters, and improve impedance matching conditions [23–26]. For example, Li et al. prepared CoNi particle-anchored N-doped carbon fibers via an impregnation-carbonization method, relying on the dielectric-magnetic loss coupling effect induced by the synergy of dual transition metal components, the material exhibited an excellent minimum reflection loss ( $RL_{\min}$ ) of  $-59.43$  dB and an effective absorption bandwidth (EAB) of  $8.5$  GHz [27]. Additionally, Co-doped SiC nanowires prepared by Liang et al. via carbothermal reduction also confirmed the key role of transition metal doping in enhancing material conductivity and magnetic response, achieving an  $RL_{\min}$  of  $-50$  dB and an EAB of  $4.0$  GHz [28]. However, commonly used doping methods like solid-state reaction and combustion synthesis are often difficult to control and require harsh conditions, hindering the controllable fabrication of complex porous structures [24, 29, 30].

Preparation of SiC/C using silicon-based polymers as ceramic precursors through specific processes enables uniform mixing of silicon and carbon elements, reduces required heat treatment temperatures, and provides excellent processability. Commonly used silicon-based precursors include polycarbosilane (PCS), polysilazane (PSZ), and polysiloxane [31–36]. For example, Wang et al. prepared low-density SiC/C aerogels using polysilazane as the precursor and phenolic resin as a cross-linking agent, which demonstrated good microwave absorption properties with an  $RL_{\min}$  of  $-31.6$  dB and an EAB of  $3.85$  GHz [37]. Although these polymer precursors exhibit relatively high ceramic yields (typically ranging from 60% to 80%, some even reaching nearly 90%), the addition of initiators or curing agents during the curing process, coupled with the evolution of small molecular byproducts during pyrolysis makes precise control over the pore channel structure challenging [38–44]. Silicon-arylacetylene resin (PSA), a high-temperature-resistant resin with a backbone consisting of alternating diethynylbenzene and silane units, undergoes reactions like cyclotrimerization and Diels–Alder (DA) reactions during curing, forming a dense cross-linked network [45–47]. Consequently, its cured product possesses excellent thermal stability and extremely high char yield, enabling the formation of a SiC/C ceramic structure upon high-temperature

pyrolysis, making it an ideal precursor resin [48, 49].

In this work, a polymer-derived synthesis strategy was developed using PSA as the matrix and cobalt acetylacetonate ( $\text{Co}(\text{acac})_3$ ) as the Co source. A precursor solution with a homogeneous cross-linked structure was constructed via a thiol-yne click reaction combined with Co-alkyne coordination. This precursor was subsequently subjected to ambient-pressure gelation, axial freezing, drying, and final high-temperature pyrolysis, ultimately yielding a Co-doped SiC/C aerogel (Co-SiC/C) with a three-dimensional porous architecture. The polymerization and cross-linking mechanism of PSA provides an ideal platform for the homogeneous introduction and catalytic effect of Co. The structure of the Co-doped SiC/C aerogels was characterized using X-ray diffraction (XRD), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), and electron paramagnetic resonance (EPR). In addition, density functional theory (DFT) calculations were employed to elucidate the modulation mechanism of Co doping on the electronic structure of the SiC/C. Furthermore, the influence of the Co doping concentration on the morphology, electromagnetic characteristics, impedance matching, and microwave absorption performance of aerogel was systematically investigated. The results indicate that within a certain range, Co doping significantly improves the impedance matching of the SiC/C aerogels, leading to excellent microwave absorption performance. The  $RL_{\min}$  reaches  $-61.51$  dB, and the EAB extends to  $4.70$  GHz. This study provides an innovative and valuable pathway for developing transition metal-doped SiC/C wave-absorbing materials and offers a new material design and preparation strategy for developing next-generation lightweight, broad-bandwidth, and high-efficiency absorbers suitable for extreme environments.

## 2 Experimental

### 2.1 Materials

Cobalt acetylacetonate ( $\text{Co}(\text{acac})_3$ ), mercaptopropyl-triethoxysilane (MPTES), azobisisobutyronitrile (AIBN), tetramethylorthosilicate (TMOS), and 1,4-dioxane were provided by Shanghai Titan Scientific Co., Ltd., China. Silicon-containing arylacetylene resin (PSA) was prepared according to the previously published work (Scheme S1 in the Electronic Supplementary Material (ESM)), presenting as a reddish-brown viscous liquid at room temperature,  $M_n = 1454$  [50].

### 2.2 Preparation of Co-doped SiC/C aerogels

Except for the hydrolysis step, all reaction operations were carried out under anhydrous and anaerobic conditions. PSA ( $13.98$  g), AIBN ( $0.41$  wt.% relative to the mass of PSA,  $0.5737$  g), 1,4-dioxane ( $1.8$  mol,  $158.40$  g), and  $\text{Co}(\text{acac})_3$  with different masses were added to a  $250$  mL three-necked flask equipped with a reflux condenser and a pressure-equalizing dropping funnel. The mixture was stirred for  $0.5$  h until complete dissolution. Subsequently, MPTES ( $0.06$  mol,  $14.28$  g) and TMOS ( $0.12$  mol,  $18.24$  g) were added dropwise to the system. The temperature was raised to  $105$  °C and maintained for  $6$  h. The mixture was then cooled to  $45$  °C and held for  $12$  h. Deionized water ( $0.66$  mol,  $11.88$  g) was added dropwise, followed by heating to  $145$  °C under reflux for  $0.5$  h to ensure complete hydrolysis, yielding the precursor solution.

The precursor solution was transferred to a mold and kept at room temperature ( $25 \pm 2$  °C) for  $24$  h until the system gelled. Subsequently, it was freeze-dried to obtain an aerogel. The aerogel was cured according to the following program:  $150$  °C/ $2$  h,  $170$  °C/ $2$

h, 210 °C/2 h, and 250 °C/4 h. The cured aerogel was subjected to high-temperature carbonization at 800 °C for 2 h under a nitrogen atmosphere, with a heating rate of 5 °C/min. Then, pyrolysis and carbothermal reduction were carried out under an argon atmosphere with a heating rate of 10 °C/min, kept at 700, 1000, 1200 °C for 2 h respectively, and finally kept at 1500 °C for 4 h to obtain the Co-doped SiC/C aerogel. The Co doping content was precisely controlled by varying the initial amount of Co(acac)<sub>3</sub>. The resulting Co-SiC/C samples were designated as C1, C2, C2.5, C3 and C3.5, corresponding to Co/PSA mass ratios of 10%, 20%, 25%, 30%, and 35%, respectively. An undoped SiC/C aerogel was synthesized under identical conditions as a control.

### 2.3 Characterization

The microstructure, morphology, heat resistance, and elemental composition of the samples were characterized using XRD (Bruker, D8), Raman spectroscopy (Thermo Fisher Scientific, DXR3xi), XPS (Thermo Fisher Scientific, ESCALAB 250Xi), EPR (Bruker, EMX-8/2.7), field emission scanning electron microscopy (SEM; HITACHI, S-4800), transmission electron microscopy (TEM; JEOL, JEM-F200), energy-dispersive X-ray spectroscopy (EDS; HITACHI, S-4800), inductively coupled plasma optical emission spectrometry (ICP-OES; Agilent, 5800 VDV), thermalgravimetric analyzer (TGA; NETZSCH, TG209F1) and mercury intrusion porosimetry (Micromeritics, AutoPore IV 9500). C3 was subjected to microstructure characterization as a representative of the Co-SiC/C aerogels. The electromagnetic parameters of the samples in the 2–18 GHz frequency range were measured using the coaxial method with a vector network analyzer (Agilent, N5230A) and a coaxial fixture. Prior to testing, concentric rings with an inner diameter of 3 mm, an outer diameter of 7 mm, and a thickness of 3 mm were prepared using paraffin as a binder. The formulas for calculating the microwave absorption performance are provided in the Section S1.2 in the ESM. Detailed simulations based on density functional theory are described in the Section S1.3 in the ESM. For the radar cross-section (RCS) simulation, the absorber model was a 50 mm × 50 mm square structure coated on a 5 mm-thick perfect electric conductor (PEC) layer. The specific calculation formulas are detailed in the Section S1.4 in the ESM.

## 3 Result and discussion

### 3.1 Preparation, microstructure, and morphology of the Co-SiC/C aerogel

Co-doped SiC/C aerogels with a porous architecture were successfully prepared using PSA as the precursor and Co(acac)<sub>3</sub> as the Co source (Fig. 1). During the precursor synthesis, the abundant alkyne groups in PSA first participated in a rapid thiol-

yne click reaction and coordinated with Co ions, forming an initial micro-crosslinked network. Simultaneously, hydrolysis of the siloxane groups constructed a Si-O-Si structure, collectively driving the gelation of the system. In the subsequent curing stage, the unreacted alkyne groups further underwent cyclotrimerization and DA reactions, resulting in a densely cross-linked three-dimensional skeleton. The high thermal stability and high char yield of PSA system (thermal resistance properties are shown in Fig. S1(a) and Table S1 in the ESM) effectively preserved this three-dimensional architecture during the high-temperature ceramization process (the specific structural evolution is shown in Fig. S2 in the ESM), ultimately yielding a high-temperature-resistant Co-doped SiC/C aerogels (Fig. S1(b) in the ESM) with intact pore channels and a well-maintained skeletal structure, exhibiting a density of approximately 0.230 g/cm<sup>3</sup> (Table S2 in the ESM). ICP-OES analysis revealed that Co content in the doped aerogels progressively increased with rising Co(acac)<sub>3</sub> loading, enabling precise control over Co doping levels (Table S3 in the ESM).

The crystal structure of the SiC/C aerogel before and after Co doping was characterized by XRD, as shown in Fig. 2(a) and Fig. S3 in the ESM. The diffraction peaks of the Co-SiC/C sample correspond well to the (111), (200), (220), (311), and (222) crystal planes of the standard 3C-SiC card (PDF #75-0254), indicating the successful formation of the 3C-SiC crystalline phase [51]. Compared with the undoped sample, the intensity of the broad diffraction peak in the Co-SiC/C sample within the 20°–30° range, which is attributed to amorphous carbon, is significantly reduced. This suggests that Co doping promotes the transformation of the carbon matrix from short-range order to long-range ordered graphitic microcrystals, thereby increasing the graphitization degree [52]. Furthermore, the intensity ratio of the stacking fault diffraction peak at 33.6° to the diffraction peak at 41.4° ( $I_{33.6}/I_{41.4}$ ) decreases markedly, indicating a reduced density of stacking faults within the SiC lattice. Notably, a slight shift is observed in the (111) diffraction peak after Co doping, which may be attributed to lattice distortion caused by the substitution of Si vacancies by larger Co atoms (Fig. 2(e)).

EPR spectroscopy was conducted to gain further insight into the defect structures. The EPR spectrum of the undoped SiC/C aerogel (Fig. 2(d)) shows a symmetric signal at  $g = 2.0027$ , characteristic of negatively charged silicon vacancies ( $V_{Si}$ ), confirming abundant intrinsic point defects [53]. This signal intensity diminishes markedly upon Co doping, implying that Co atoms effectively occupy the  $V_{Si}$  sites, passivating these point defects. Raman spectroscopy results (Fig. 2(b) and Fig. S4 in the ESM) further elucidate the regulatory effect of Co doping on the matrix. Compared to the SiC/C (with an  $I_D/I_G$  value of 2.43), all Co-doped aerogels exhibit a significant reduction of  $I_D/I_G$ , demonstrating a significant enhancement in the graphitization degree of the carbon

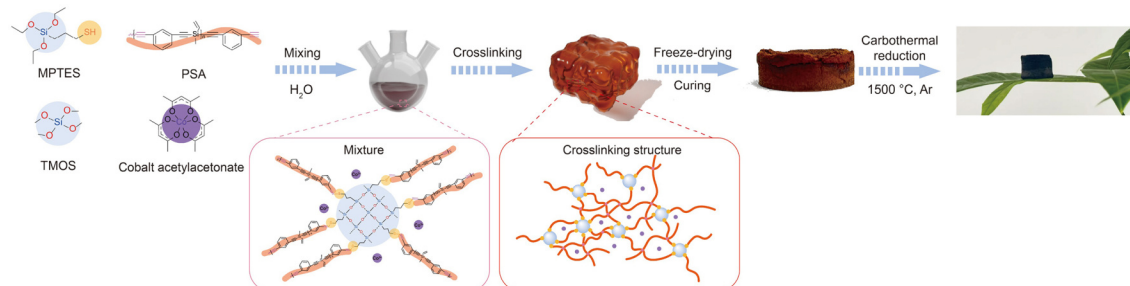


**Figure 1** Preparation method for the Co-SiC/C aerogel.

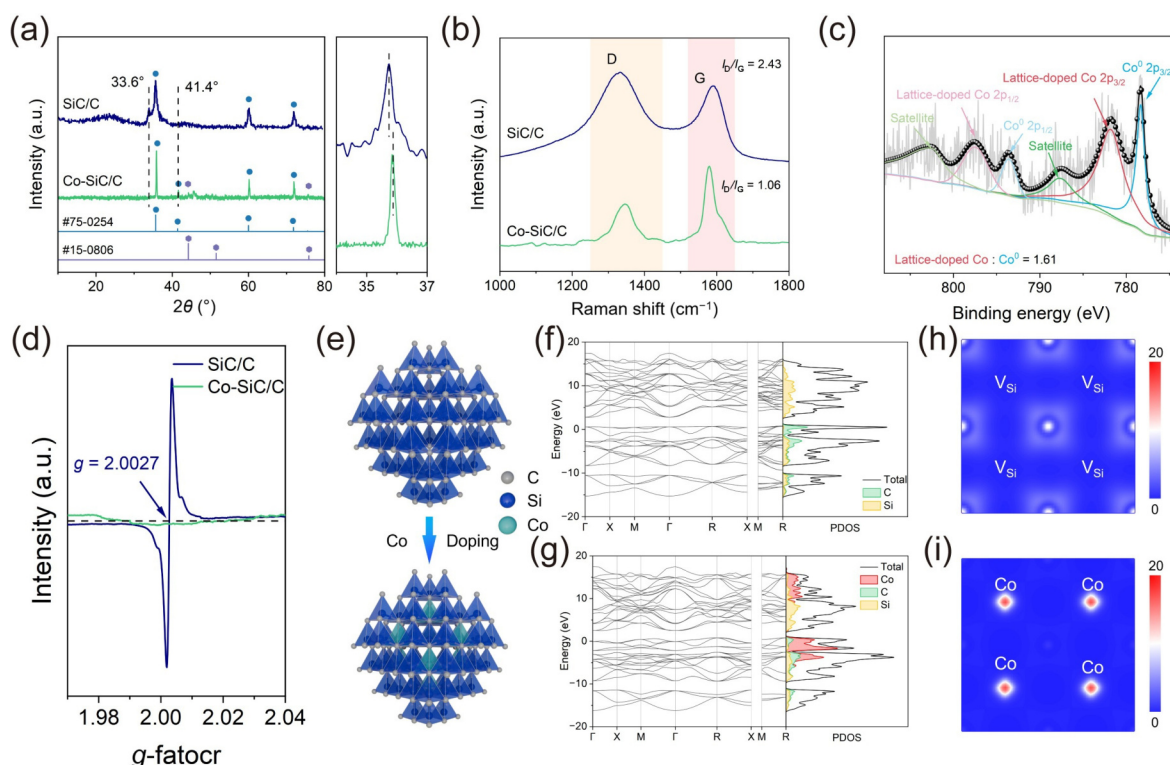


**Figure 2** Structural characterization of Co-doped SiC/C aerogel: (a) XRD patterns, (b) Raman spectra, (c) XPS spectrum, (d) EPR, and (e) lattice structure of Co-doped  $V_{Si}$ . Electronic band structure, density of states, and electron distribution: (f) and (h) undoped, (g) and (i) Co-doped.

matrix [54, 55]. Specifically, as Co content increases, the  $I_D/I_G$  value exhibits a trend of first decreasing and then increasing, falling continuously from 1.55 at C1 to 1.06 at C3. However, when Co content increases further, the  $I_D/I_G$  value rises to 1.23. This indicates that excessive Co may disrupt the continuity of the carbon network, leading instead to increased disorder in the carbon matrix. Concomitantly, the emergence of a D' shoulder peak around  $1615\text{ cm}^{-1}$  suggests that Co doping also introduces new localized defects alongside the improved overall structural order.

The influence of Co doping on the electronic states of the SiC/C aerogel was analyzed by XPS, with the results presented in Fig. 2(c) and Fig. S5 in the ESM. In the Co 2p spectrum, alongside the characteristic peaks for lattice-doped Co located at 779.8 and 795.0 eV, signals corresponding to zero-valent Co ( $Co^0$ ) were also observed at 778.3 and 792.5 eV [56, 57]. This indicates the partial reduction of Co to its metallic state during the high-temperature synthesis process. The presence of these nanoparticles increases the number of heterogeneous interfaces within the aerogel, thereby introducing magnetic response characteristics to the originally purely dielectric SiC/C aerogel. This contribution is conducive to enhancing magnetic loss and optimizing impedance matching. Quantitative analysis based on the Co  $2p_{3/2}$  peak area (Fig. S5 in the ESM) revealed that the ratio of lattice-doped Co to metallic Co decreased from 2.19 in C1 to 1.07 in C3.5 as the Co loading increased. This trend indicates that Co preferentially occupies  $V_{Si}$  within the lattice, whereas excess Co undergoes carbothermic reduction to form metallic Co.

To understand the doping mechanism of Co at the electronic structure level, DFT calculations were performed on a 3C-SiC model with Co occupying a  $V_{Si}$ . Band structure analysis reveals that the intrinsic 3C-SiC containing  $V_{Si}$  is a direct bandgap semiconductor, with both the valence band maximum and

conduction band minimum located at the  $\Gamma$  point. After Co doping, its 3d orbitals introduce new electronic states near the Fermi level, endowing the system with a metallic character. Density of states (DOS) analysis (Fig. 2(f)) indicates that Co doping increases the total DOS at the Fermi level to 1.6 states/eV. The projected density of states (PDOS) results demonstrate that these electronic states primarily originate from the Co-3d orbitals, with minimal contributions from C and Si, indicating that the electronic states of Co dominate the characteristics near the Fermi surface. Electron density difference maps (Figs. 2(h) and 2(i)) visually demonstrate a significant increase in electron density in the Co-doped region, further confirming that Co, through the introduction of its active 3d electrons, effectively modulates the electronic structure of SiC/C, induces a metallic transition, and enhances the charge carrier concentration [58].

The microstructure and elemental composition of the samples were characterized using SEM, high-resolution TEM (HRTEM), and EDS, with the results shown in Figs. 3(a) to 3(e) and Fig. S6 in the ESM. The results indicate that the porous skeleton constructed via axial freezing is predominantly composed of honeycomb-like macropores, with nanowires and nanospheres uniformly distributed within the aerogel. Pore size distribution analysis via mercury intrusion porosimetry (Fig. S7 and Table S4 in the ESM) shows that the Co-SiC/C aerogels (C1, C2, C2.5, and C3) have an average pore size of 34.4, 38.7, 40.9, and 45.0  $\mu\text{m}$ , respectively, with porosities of 62.0%, 63.5%, 64.3% and 67.1% (all exceeding 60%). Co doping content exhibits a significant regulatory effect on the porous structure. Specifically, C2 and C2.5 display not only macropores but also a number of mesopores and micropores, resulting in a notable increase in specific surface area to 95.1 and 100.6  $\text{m}^2/\text{g}$ . This is primarily attributed to the nucleation effect of Co, which promotes the formation of finer-scale pore structures.

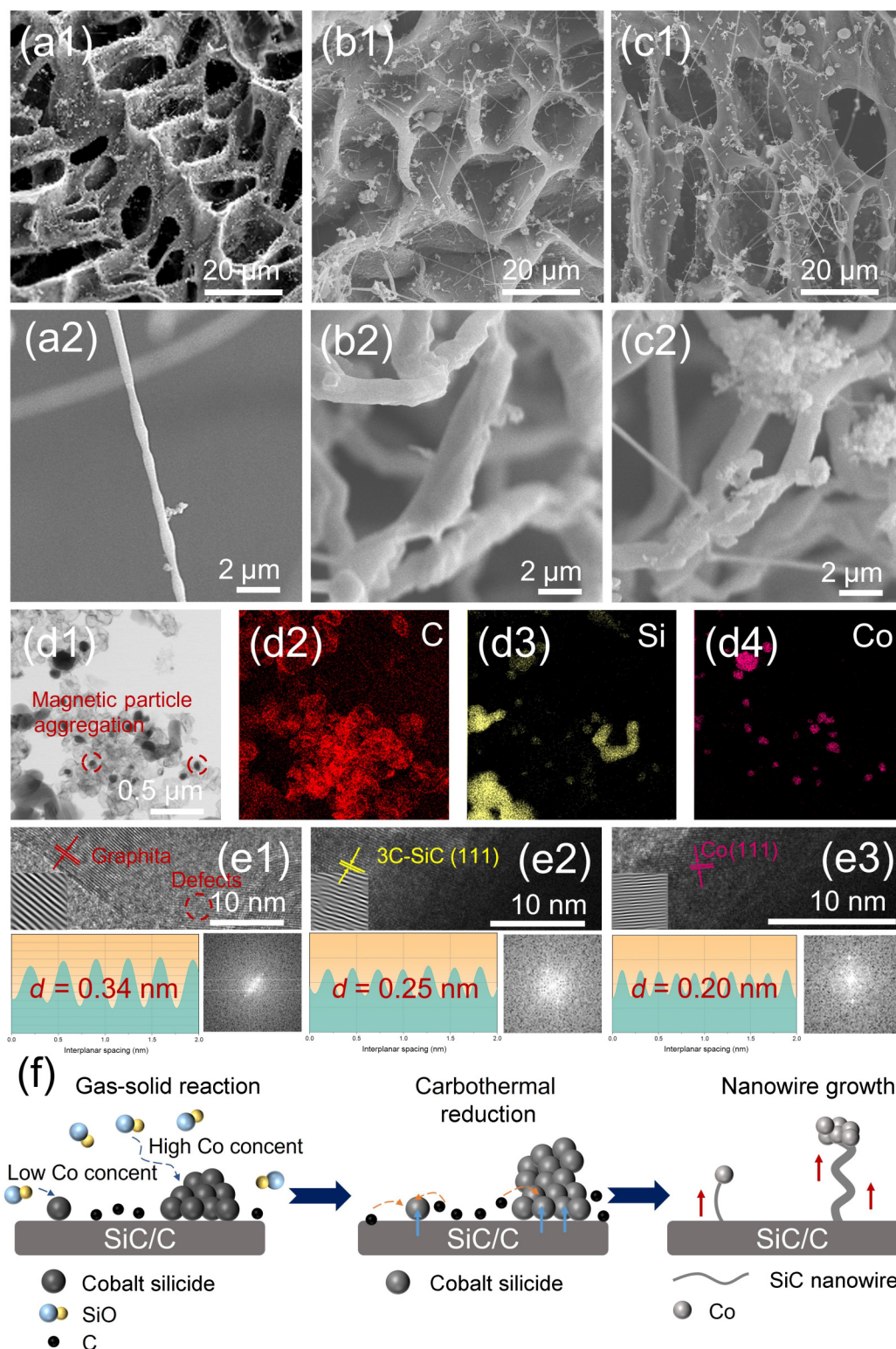


**Figure 3** Morphology and crystal structure characterization of the Co-doped aerogels. SEM images: (a1) and (a2) C1, (b1) and (b2) C2, (c1) and (c2) C3. TEM analysis: (d) elemental mapping, HRTEM images showing lattice fringes of: (e1) graphitic carbon, (e2) 3C-SiC, and (e3) Co. (f) Schematic illustration of the carbon nanowire growth process.

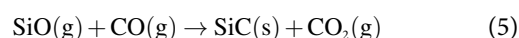
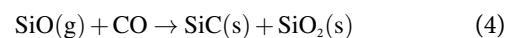
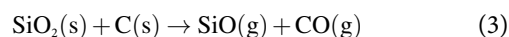
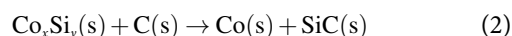
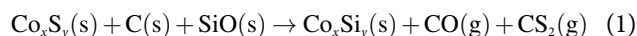
However, as the Co content further increases, the average pore size, porosity, and pore volume increase considerably, leading to a reduction in specific surface area. SEM images (Fig. 3(c)) reveal minor structural fractures in the pores of sample C3. It is inferred that excessive Co doping may catalyze and accelerate the hydrolysis

and cross-linking reactions during aerogel formation, thereby inducing pore coarsening. Meanwhile, excessive Co catalyzing overly rapid gelation, resulting in a network skeleton of uneven strength. During subsequent drying and pyrolysis, this fragile network partially collapsed and densified, severely damaging the

pore structure of C3.5 and transforming it into a loose accumulation of dense aggregates.

Furthermore, with increasing Co doping content, the number of nanowires within the system gradually increases, and their morphology evolves from straight rods (100–300 nm) to worm-like structures (1–2  $\mu\text{m}$ ). The presence of Co nanoparticles in Co-SiC/C is confirmed in C2 (Fig. 3(b2)). The HRTEM image in Fig. 3(e3) reveals lattice fringes with a spacing of 0.20 nm, corresponding to the Co(111) plane [59]. Lattice spacings of 0.34 and 0.25 nm observed in Figs. 3(e1) and 3(e2) further confirm the existence of graphitic carbon and the 3C-SiC phase, respectively [60, 61]. Notably, partial distortion of diffraction fringes is observed in the 3C-SiC, which can be attributed to lattice deformation resulting from the incorporation of Co into the SiC crystal lattice. Based on HRTEM images and XRD patterns (Fig. S2 in the ESM) of precursors at different temperatures, the growth and transformation of the nanowires can be summarized by reactions (Eqs. (1) to (5)):  $\text{Co}(\text{acac})_3$  reacts with S element at high temperature to form cobalt sulfide ( $\text{Co}_x\text{S}_y$ ), which subsequently reacts with C and SiO to form cobalt silicide ( $\text{Co}_x\text{Si}_y$ ). The silicide is then reduced by carbon at high temperature, generating supersaturated Co-doped SiC crystal nuclei and metallic Co particles. These nuclei continue to grow via a vapor-solid mechanism, ultimately forming worm-like SiC nanowires and promoting the formation of the 3C-SiC crystalline phase, as illustrated in Fig. 3(f). EDS mapping results (Fig. S6 in the ESM) demonstrate a homogeneous distribution of C, Si, and Co elements within the system. Metallic Co that did not incorporate into the SiC lattice tended to agglomerate at high temperature, existing as particles attached to the SiC/C surface, thereby forming heterogeneous interfaces. According to polarization resonance theory, different crystal planes or orientations typically lead to alterations in electronic energy bands and intracrystalline interface coupling, thereby inducing differential energy band reorganization, which

enhances dipole relaxation and interfacial polarization [62, 63]. Additionally, the abundant point defects within the graphitic carbon also contribute to enhanced dipole and interfacial polarization.



### 3.2 Electromagnetic parameters of the Co-doped SiC/C aerogel

In microwave absorbing materials, the electromagnetic response characteristics are primarily determined by the electromagnetic parameters. To systematically investigate the electromagnetic response characteristics of Co-SiC/C aerogels with different Co contents, the complex permittivity and complex permeability of C1, C2, C2.5, C3, and C3.5 were measured using the coaxial method. Figure 4(a) displays the real part ( $\epsilon'$ ) and imaginary part ( $\epsilon''$ ) of the complex permittivity. Evidently, the  $\epsilon'$  values of C1, C2, C2.5 and C3 decrease with increasing frequency, exhibiting typical frequency dispersion behavior. Specifically, the  $\epsilon'$  values of C1–C3 decrease from 6.67 to 6.26, 8.59 to 7.60, 9.90 to 8.23 and 13.89 to 11.77, respectively. A gradual increase in the value of  $\epsilon'$  is observed from C1 to C3 with increasing Co doping content, indicating an enhanced electrical energy storage capability of the aerogel. In contrast, C3.5 exhibits a lower  $\epsilon'$  value than that of C3 and shows an unusual increase within the 2–18 GHz range. This reversed

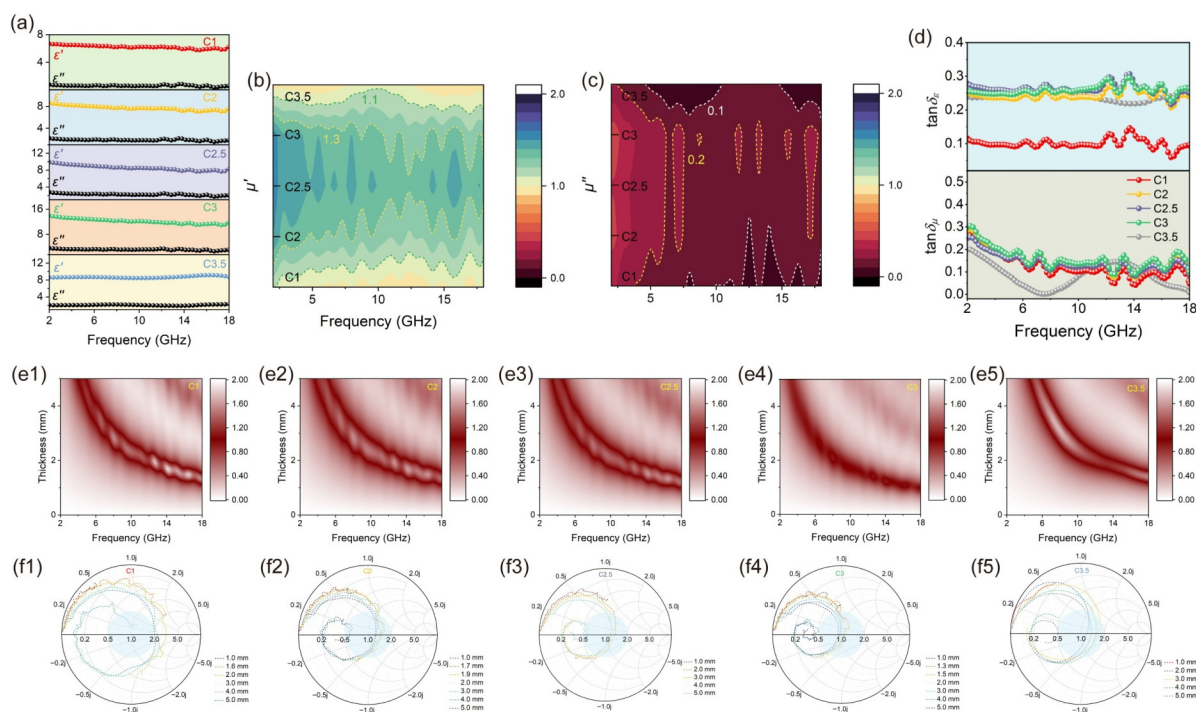


**Figure 4** (a)–(d) Electromagnetic parameters, (e) impedance matching ratio, and (f) Smith chart of samples C1, C2, C2.5, C3, and C3.5.

frequency dispersion, coupled with the overall reduction in  $\epsilon'$ , is attributed to the severe degradation of the porous structure in C3.5. The fractured structure disrupts the continuity of the conductive pathways, reduces the density of effective heterointerfaces, and consequently weakens the polarization contribution. Simultaneously, localized charge accumulation at defects and fragmented interfaces within the damaged structure may induce intense space charge polarization, leading to the  $\epsilon'$  increases resembling resonance at specific frequencies. The  $\epsilon''$  shows multiple resonance peaks within the 2–18 GHz range, indicating significant dielectric dispersion effects originating from relaxation processes associated with multiple polarization mechanisms.

To gain deeper insight into the loss mechanisms, Cole–Cole plots of the samples were depicted (Figs. S8(a)–S8(e) in the ESM). These plots typically consist of linear and semicircular regions, the linear segment is primarily attributed to conductive loss, while the arc segment corresponds to polarization loss. The results indicate that the dielectric loss in Co-doped SiC/C aerogels results from the coupled effects of conductive loss and multiple polarization mechanisms. Consequently, the total  $\epsilon''$  was deconvoluted into conductive loss ( $\epsilon_c$ ) and polarization loss ( $\epsilon_p$ ) components (Figs. S8(f)–S8(j) in the ESM) [64]. Analysis reveals that the  $\epsilon_c$  contribution decays rapidly with increasing frequency. To quantify the dominant mechanism, the geometric means of the  $\epsilon_c$ ,  $\epsilon_p$ , and their ratio were calculated (Fig. S8(k) in the ESM). The results demonstrate that polarization loss is the overall dominant dielectric loss mechanism in the Co-doped SiC/C aerogels. However, with increasing Co doping content, the contribution of  $\epsilon_c$  enhances significantly, and its proportion gradually increases (reaching a maximum of 0.51 for C3). The loss mechanism transitions from being predominantly governed by intrinsic defect-related polarization loss towards a synergistic effect involving more efficient and broader-band conductive loss and polarization loss introduced by Co. This effectively optimizes the loss structure of aerogels, favoring a more balanced broadband impedance matching. Notably, despite exhibiting the highest overall Co content, the collapse of the pore structure in C3.5 disrupts the continuity of the conductive network. This may suppress its theoretically high conductive loss potential while intensifying polarization relaxation dominated by defect interfaces, resulting in a reduced ratio compared to C3. Furthermore, the introduction of Co imparts significant magnetic loss characteristics to the originally purely dielectric SiC/C aerogel. Both the real ( $\mu'$ ) and imaginary ( $\mu''$ ) parts of the complex permeability increase with Co content and exhibit strong resonance peaks at specific frequencies (Figs. 4(b) and 4(c)). Analysis of the  $C_0$  values (Fig. S8(l) in the ESM) confirms that both eddy current loss and natural resonance collectively constitute the magnetic loss mechanisms of the aerogel [65, 66]. However, excessive Co in C3.5 causes particle agglomeration and embedding within the damaged matrix, which may weaken magnetic coupling efficiency.

Figure 4(d) shows the frequency dependence of the dielectric loss tangent ( $\tan \delta_\epsilon$ ) and the magnetic loss tangent ( $\tan \delta_\mu$ ). The  $\tan \delta_\epsilon$  values for C1, C2, C2.5 and C3 fluctuate with frequency, peaking in the 12–14 GHz range. Notably, the dielectric loss generally increases with higher Co doping ratios. This is attributed to Co doping reducing intrinsic defects within the SiC lattice and enhancing the conductive loss. Furthermore, the incorporation of Co into the SiC lattice induces lattice distortion, generating new defects which also strengthen the dipole polarization relaxation intensity, thereby improving the conversion efficiency of electrical energy to thermal

energy and enhancing energy dissipation. The  $\tan \delta_\mu$  also gradually increases with Co content, particularly in the low-frequency range, where its loss capability exceeds that of dielectric loss. However, excessive Co reduces both  $\tan \delta_\epsilon$  and  $\tan \delta_\mu$  due to structural integrity degradation. In summary, within the Co-doped SiC/C aerogels, magnetic loss dominates at low frequencies, while dielectric loss becomes dominant at high frequencies. This complementary synergistic mechanism suggests excellent microwave absorption potential across a broad frequency range.

Outstanding electromagnetic wave absorption performance relies on two core parameters: impedance matching ( $Z$ ) and the attenuation constant ( $\alpha$ ). Ideal impedance matching ( $|Z_{in}/Z_0|$  value between 0.8 and 1.2) ensures maximal wave penetration into the material rather than reflection. As shown in Fig. 4(e), Co doping significantly optimizes the impedance matching characteristics. A clear optimization trend is observed from C1 to C3, evidenced by the expanded area of the optimal matching zone and the appearance of multi-resonance matching features. However, for the over-doped sample C3.5, the matched region narrows noticeably, indicating degraded impedance matching compared to C3. This is further verified by the Smith charts (Fig. 4(f)) [67, 68]. Regarding attenuation capability, the  $\alpha$  increases markedly with Co content (Fig. S8 in the ESM), indicating a substantially enhanced loss capability. Conversely,  $\alpha$  for C3.5 is lower than that of C3, consistent with its declined electromagnetic parameters. Overall, the Co-doped SiC/C aerogels achieve exceptional broadband microwave absorption through a synergistic balance of these two parameters. Sample C3 represents the optimal condition, where significantly optimized impedance matching coincides with the most potent attenuation capability, allowing electromagnetic waves to penetrate deeply and be effectively dissipated. This is the key to their exceptional broadband microwave absorption performance.

### 3.3 Microwave absorption performance and mechanism of Co-doped SiC/C aerogels

The electromagnetic wave absorption performance of the Co-doped SiC/C aerogels was characterized using the transmission line theory. Figures 5(a)–5(c) and Fig. S9 in the ESM show the reflection loss (RL) curves of the samples from C1 to C3.5 mixed with paraffin at a 20 wt.% ratio. Analysis indicates that the Co doping content has a systematic influence on the absorption performance. For C1, while it exhibits an excellent  $RL_{min}$  of  $-25.16$  dB at a specific frequency with a matching thickness of 5.0 mm, its effective absorption bandwidth (EAB, for  $RL \leq -10$  dB) is only 1.41 GHz, demonstrating typical narrowband strong absorption characteristics. As the Co doping content increases, the microwave absorption properties are gradually enhanced. Sample C2, with a thickness of 1.9 mm, achieves an  $RL_{min}$  of  $-20.79$  dB at 4.69 GHz and a significantly broader total EAB of 4.65 GHz. Sample C2.5 shows a continued improvement trend. The best-performing sample, C3, exhibits an  $RL_{min}$  of  $-61.51$  dB at 13.10 GHz (1.5 mm) and the widest EAB of 4.70 GHz at a thin thickness of 1.3 mm, demonstrating exceptional broadband absorption capability. However, with a further increase in Co content, sample C3.5 shows a clear performance degradation, attaining an  $RL_{min}$  of only  $-22.19$  dB at 13.08 GHz with a matching thickness of 2.0 mm, which is significantly inferior to that of C3.

To further assist in verifying the impedance matching, the normalized input impedance ( $Z_{in}$ ) was analyzed. Figure S10 in the ESM shows that the impedance matching for C3 is closest to the

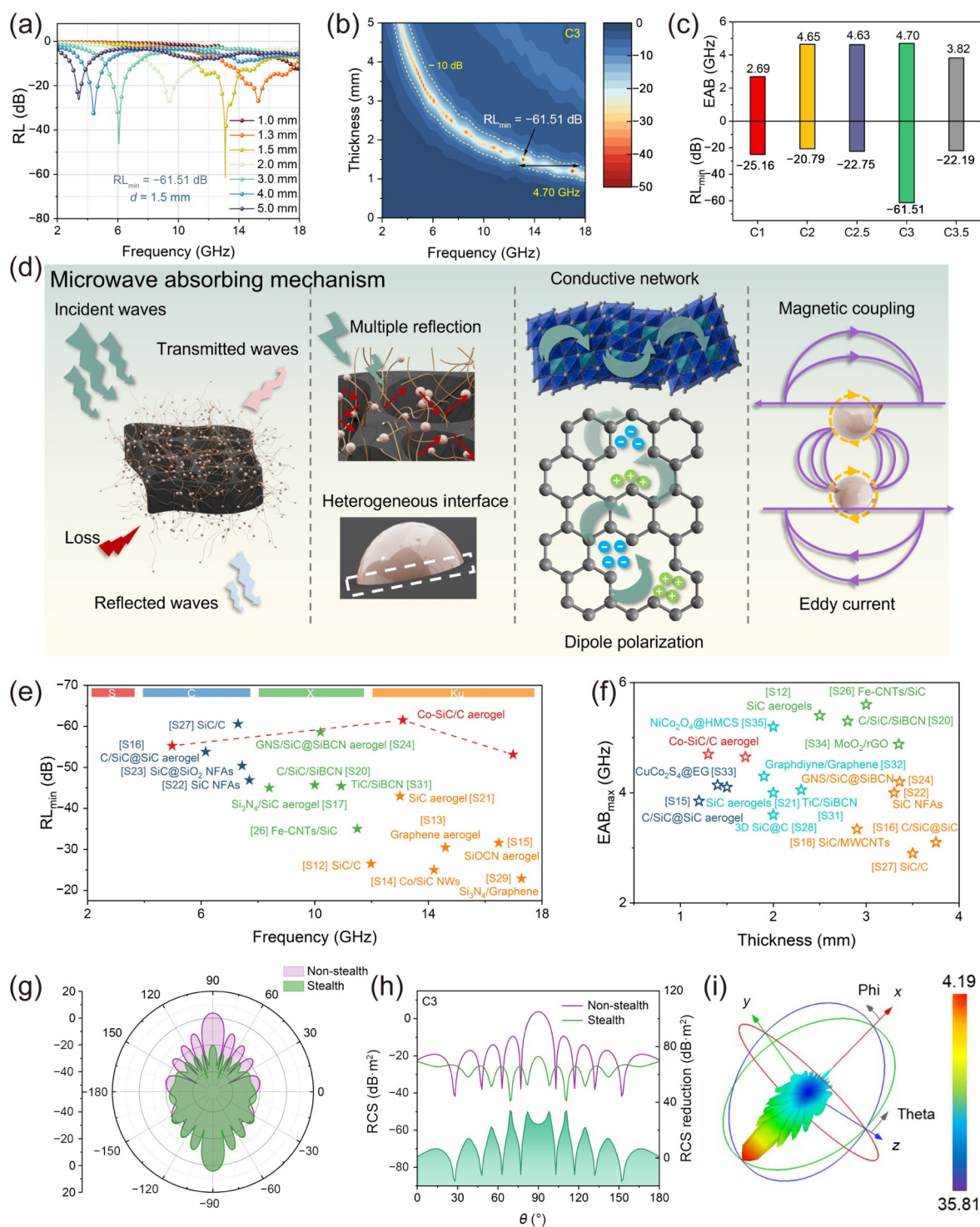


**Figure 5** (a) Reflection loss curves and (b) two-dimensional distribution of the sample C3. (c) RL<sub>min</sub> and corresponding EAB of the samples from C1 to C3.5. (d) Microwave absorbing mechanism of the Co-doped SiC/C aerogels. (e) and (f) Performance comparison of the Co-doped SiC/C aerogel and other reported microwave absorbing materials. (g) Radar cross section of C3. (h) RCS values and (i) three-dimensional distribution.

ideal condition at 13.10 GHz (corresponding to its RL<sub>min</sub>), confirming that its optimal impedance matching is the key to achieving superior performance. This is attributed to the synergistic effect of multiple loss mechanisms (conductive loss, dielectric polarization loss, magnetic loss) introduced by Co doping, which collectively optimize the impedance characteristics of the material. Compared to other reported absorbers such as silicon carbide

ceramics, carbon-based heterostructures, and metal-doped ceramics, the Co-doped SiC/C aerogel exhibits lower reflection loss in both the C-band and Ku-band.

Figure 5(d) illustrates the electromagnetic wave absorption mechanism of the Co-doped SiC/C aerogel. First, Co doping induces a synergistic effect among diverse loss mechanisms. The incorporation of Co enhances the graphitization degree of the

carbon network, improving the migration ability of charge carriers along the  $sp^2$ -hybridized carbon skeleton and SiC, thereby increasing the contribution of conductive loss. The abundant heterogeneous interfaces between SiC/C, C/Co, and SiC/Co induce strong interfacial polarization. Furthermore, defects introduced by Co promote dipole polarization, collectively optimizing the dielectric loss structure. Additionally, the natural resonance and eddy current losses contributed by the Co particles introduce significant magnetic loss mechanisms to the system. This transforms the SiC/C aerogel from a purely dielectric absorber into a dielectric-magnetic coupled one, exhibiting a characteristic division and synergy of mechanisms across different frequency bands. Secondly, the porous structure provides the foundation for optimizing impedance matching by reducing dielectric constant, thereby effectively promoting the penetration of the electromagnetic wave. Specifically, micrometer-scale macropores primarily contribute to the deep penetration of electromagnetic waves and multiple scattering at the macroscopic scale, significantly extending the propagation path to enhance attenuation [69]. In contrast, nanometer-scale pores serve as effective dielectric modulation units, enabling finer optimization of impedance matching [70]. Meanwhile, relatively high specific surface area can confine electromagnetic waves within the internal void spaces, promoting multiple reflections and interfacial polarization [71, 72]. Compared to other porous materials, this combination of pore structures confers superior absorptive performance (Table S5 in the ESM). Overall, due to the synergistic effect of multiple loss mechanisms and the optimized impedance matching provided by the porous structure, the Co-SiC/C aerogel achieves efficient electromagnetic wave absorption across a broad frequency range, demonstrating performance superior to that of most comparable materials (Figs. 5(e) and 5(f), and Tables S6 in the ESM).

To further evaluate the practical application potential of the materials, the radar cross section (RCS) of C1–C3.5 was simulated under plane wave excitation with a perfect electric conductor (PEC) as the backing plate. The results are shown in Figs. 5(g)–5(i) and Fig. S11 in the ESM. The 3D-RCS results indicate that the radar signal attenuation capability of C3 is significantly stronger than that of C1, C2, C2.5, and C3.5. The one-dimensional RCS results clearly show that at a  $90^\circ$  incident angle, samples C3 achieve RCS reductions of  $-33.45 \text{ dB}\cdot\text{m}^2$  at 13.10 GHz, respectively, compared to the PEC substrate. Notably, C3 achieve significant attenuation of the RCS signal strength across different frequencies (Fig. S12 in the ESM). Furthermore, their radiation pattern shows a substantial reduction in the reflected signal across almost the entire detection space, indicating that the electromagnetic energy is effectively dissipated within the material [73]. In summary, the Co-doped SiC/C aerogels demonstrate comprehensive advantages, including strong absorption, broad bandwidth, good impedance matching, and low RCS, indicating that they are highly promising high-performance electromagnetic wave absorbing materials. It shows promising application prospects in unmanned aerial vehicle (UAV) fuselage coatings, radome protection, and core materials of aerospace sandwich structures.

## 4 Conclusion

Overall, this study successfully demonstrates a polymer-derived strategy for synthesizing Co-doped SiC/C aerogels. The incorporation of Co not only enhances conductive loss and optimizes dielectric loss through lattice doping but also introduces magnetic loss via metallic nanoparticles, while simultaneously

catalyzing the growth of worm-like SiC nanowires to construct multi-scale heterogeneous interfaces. As a result, the doped aerogel exhibits exceptional microwave absorption performance, achieving a minimum reflection loss of  $-61.51 \text{ dB}$  at 13.10 GHz and an effective absorption bandwidth of 4.70 GHz at an ultra-thin thickness of 1.3 mm. Radar cross-section simulations further confirm its practical potential for stealth applications. This work provides an innovative pathway for designing transition-metal-doped porous ceramic aerogels with tailored electromagnetic properties, holding broad significance for the development of advanced electromagnetic protection materials suitable for extreme environments, and can be further applied to the development of military stealth components, electromagnetic compatibility devices for high-power electronic equipment, and lightweight microwave-absorbing structures for near-space detectors.

**Electronic Supplementary Material:** Supplementary material (structure, morphological characterization, electromagnetic properties, and RCS simulation results of the samples) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908615>.

## 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

The authors declare no competing financial interest.

## Author contribution statement

C. N. J.: Conceptualization, data curation, formal analysis, investigation, visualization, writing – original draft. Y. X. Z.: Data curation, methodology, software. C. Q. Z.: Formal analysis, methodology. L. J. S.: Investigation, methodology. H. M. Z.: Methodology, software. J. Y. Z.: Data curation, Investigation. X. S. Z.: Conceptualization, writing – review and editing. F. W.: Project administration, validation. Y. P. Z.: Supervision, writing – review and editing. S. F. D.: Conceptualization, resources. H. M. Q.: Conceptualization, funding acquisition, writing – review and editing. All the authors have approved the final manuscript.

## Use of AI statement

None.

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