Microwave induced *in-situ* formation of SiC nanowires on SiCNO ceramic aerogels with excellent electromagnetic wave absorption performance

Keke YUAN^{a,†}, Daoyang HAN^{a,†}, Junfang LIANG^a, Wanyu ZHAO^b,
Mingliang LI^{a,*}, Biao ZHAO^c, Wen LIU^a, Hongxia LU^a,
Hailong WANG^a, Hongliang XU^a, Gang SHAO^{a,*}, Rui ZHANG^{a,d}

^aSchool of Materials Science and Engineering, Zhengzhou University, Zhengzhou 450001, China

^bThe 27th Research Institute of China Electronic Technology Group Corporation, Zhengzhou 450047, China

^cHenan Key Laboratory of Aeronautical Material and Application Technology, School of Materials Science and Engineering, Zhengzhou University of Aeronautics, Zhengzhou 450046, China

^dSchool of Materials Science and Engineering, Luoyang Institute of Science and Technology, Luoyang 471023, China

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Abstract: Electromagnetic absorption (EMA) materials with light weight and harsh environmental robustness are highly desired and crucially important in the stealth of high-speed vehicles. However, meeting these two requirements is always a great challenge, which excluded the most attractive lightweight candidates, such as carbon-based materials. In this study, SiC_{nw}-reinforced SiCNO (SiC_{nw}/SiCNO) composite aerogels were fabricated through the *in-situ* growth of SiC_{nw} in polymer-derived SiCNO ceramic aerogels by using catalyst-assisted microwave heating at ultra-low temperature and in short time. The phase composition, microstructure, and EMA property of the SiC_{nw}/SiCNO composite aerogels were systematically investigated. The results indicated that the morphology and phase composition of SiC_{nw}/SiCNO composite aerogels can be regulated easily by varying the microwave treatment temperature. The composite aerogels show excellent EMA property with minimum reflection loss of −23.9 dB@13.8 GHz, −26.5 dB@10.9 GHz, and −20.4 dB@14.5 GHz and the corresponding effective bandwidth of 5.2 GHz, 3.2 GHz, and 4.8 GHz at 2.0 mm thickness for microwave treatment at 600 °C, 800 °C, and 1000 °C, respectively, which is much better than that of SiCN ceramic aerogels. The superior EMA performance is mainly attributed to the improved impedance matching, multi-reflection, multi-interfacial polarization, and micro current caused by migration of hopping electrons.

Keywords: polymer-derived SiCNO ceramic aerogel; SiC nanowires (SiC_{nw}); microwave heating; electromagnetic absorption (EMA) performance

† Keke Yuan and Daoyang Han contributed equally to this work.

* Corresponding authors.

E-mail: M. Li, bright_de@zzu.edu.cn;

G. Shao, gang_shao@zzu.edu.cn

1 Introduction

Recently, tremendous efforts have been devoted to developing excellent electromagnetic absorption (EMA) materials for electronic safety and defense stealth technology [1,2]. The ideal EMA materials are required with the properties of light weight, broad band, strong absorption, and thinness [3–5]. Owing to large density, narrow band width, and easy oxidation, traditional EMA materials, such as ferrite [6], magnetic metal powders [7], and carbon materials [8] cannot meet the absorption demands. To achieve good EMA properties, the materials should be composed of electrical insulating phase and an electric and/or dielectric loss phase for providing good impedance matching and EM attenuation ability, as well as multiple phases and multi-dimensional structures, to further improve the EMA properties by additional interfacial polarization and multi-reflection of microwaves.

Polymer-derived SiCN ceramics (PDC-SiCN) possess excellent thermal mechanical property and oxidation/corrosion resistance [9–11], and owing to their easily-tunable microstructure and composition [12], especially the carbon dangling-bonds in SiCN matrix [13,14], the EMA property of PDC-SiCN is also excellent, such as SiCN [15] and SiBCN/graphene@Fe₃O₄ [16]. These studies show excellent EMA abilities of PDCs due to their high dielectric and/or electric loss. However, the previous studies all focus on dense and/or low porosity bulky materials, meaning that the density needs to be further decreased to meet the requirement of “lightweight”.

PDC aerogels synthesized in our previous work present ultralow density (0.19 g/cm³) and excellent EMA properties, due to the multiple reflections of EM waves in 3D porous structures and interfacial polarization [17]. However, as the drawbacks of all kinds of ceramic aerogels, the PDC aerogels are also fragile. In order to improve the mechanical property of PDC aerogels, in-situ growth of 1D SiC nanowires (SiC_{nw}) in aerogels is proposed; moreover, it is beneficial to establish nano-heterogeneous interfaces for strengthening interface polarization, and improve the absorbing ability finally [18]. Usually, the growth of SiC_{nw} or SiC whiskers in PDCs requires high temperature (> 1400 °C) and long time either with or without catalyst [19–21], and an effective way to produce 1D nanowires in PDCs is desirable.

The present work suggests a viable methodology for the fabrication of SiC_{nw}-reinforced SiCNO (SiC_{nw}/SiCNO)

composite aerogels using Fe as catalyst in the microwave heating process. The effects of microwave-treated temperature on microstructure evolution, dielectric and EMA properties of SiC_{nw}/SiCNO composite aerogels were investigated. The hierarchical architecture combined with SiC_{nw} and 3D framework in aerogels was demonstrated to enhance the EMA. Meanwhile, the formation mechanisms of hierarchical architecture during the microwave heating and the microwave absorption mechanisms of SiC_{nw}/SiCNO composite aerogels were also discussed in details.

2 Experimental procedure

2.1 Preparation of SiC_{nw}/SiCNO composite aerogels

The PDC-SiCN aerogels were fabricated by combining the freeze-drying technique and PDC route similar to our previous study [17], specifically, which were obtained via pyrolysis in N₂ atmosphere at 1000 °C and named as PDCA-SiCN. The prepared PDCA-SiCN was immersed in the acetone solution of ferrocene (Fe(C₅H₅)₂; Fengchuan Chemical Reagent Co., Ltd., China) with concentration of 5 mg/mL overnight and then dried naturally at room temperature. The ferrocene-modified PDCA-SiCN was heat treated in a microwave-material workstation (MobileLab, Tangshan Nano Source Microwave Thermal Instrument Manufacturing Co., Ltd., China) without any aided heaters at 600, 800, and 1000 °C for 10 min with a heating rate of 30 °C/min under ultrahigh-purity N₂ flow, which were named as mw-600, mw-800, and mw-1000, respectively.

2.2 Characterization

The crystalline structure of the aerogels was identified by X-ray diffraction (XRD; SmartLab, Rigaku Instrument Corp., Japan) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). The morphology and element mapping of the aerogels were characterized by field emission scanning electron microscopy (FE-SEM; Quanta FEG 250, FEI Co. Ltd., USA) equipped with energy dispersive spectroscopy (EDS). Transmission electron microscopy (TEM) of the composite aerogels was performed using a TecnaiG2 F20 instrument (FEI Co., Ltd., the Netherlands) operating at an acceleration voltage of 200 kV. Laser Raman spectroscopy was attained by a MicroRaman spectrometer (LabRAM HR Evolution, Horiba Jobin

Yvon Co., Ltd., Japan) with the 532 nm line of silicon-solid laser as the excitation source. The porosity of the aerogels was analyzed by N₂ adsorption/desorption experiments (ASAP 2020 system, Micromeritics Instrument Corp., USA) at 77 K. Specific surface area (SSA) and pore size distribution were calculated by employing the Brunauer–Emmett–Teller (BET) method and the Barrett–Joyner–Halenda (BJH) method, respectively. The relative complex permeability and permittivity of the sample–paraffin wax composite were determined by the coaxial line method through a vector network analyzer system at 2–18 GHz range (Agilent N5234A, Agilent Technologies Inc., USA). The samples are mixed evenly with paraffin wax at 88% weight proportion, and the mixture is pressed into a coaxial ring with an inner diameter of 3 mm and an outer diameter of 7 mm. According to the transmission line theory, the reflection loss (RL) of the composites can be calculated based on the measured data of relative complex permeability and permittivity.

3 Results and discussion

3.1 Microstructure of SiC_{mw}/SiCNO composite aerogels

Figure 1 shows the morphologies of as-prepared

PDC-SiCN aerogels and SiCN composite aerogels at different microwave heating temperatures. As is seen in Fig. 1(a), the PDC-SiCN aerogels possess 3D framework, the hierarchical pores range from mesopores to macropores, and the SiCN particles are smaller than 100 nm. After ferrocene-modified PDC-SiCN aerogels were heat treated using microwave heating technology at 600 °C, some short whiskers wrapped on the surfaces of SiCN ceramic matrix were observed (Fig. 1(b)). As the temperature increased to 800 °C, as shown in Fig. 1(c), plenty of nanorods grew in void spaces of SiCN particles. Figure 1(d) shows the morphologies of SiCN aerogels after 1000 °C microwave heating, which displays that large numbers of nanowires generated upon SiCN matrix.

The composition of 1D nanostructure in PDC-SiCN aerogels was measured using EDS, and the typical EDS spectra obtained from the samples of mw-600, mw-800, and mw-1000 are presented in Fig. 2, which reveals that the 1D nanostructure consists of Si, C, and Fe elements and the distribution of Fe element is rather uniform; moreover, a small amount of N and O elements in SiCN matrix are also observed. Observations from high resolution image (Fig. 2) reveal that the 1D nanostructures exhibit a cylindrical shape with smooth surfaces. The average diameters are 25, 35, and 30 nm

Fig. 1 SEM images of (a) SiCN aerogels and SiCN composite aerogels prepared by microwave heating at (b) 600 °C, (c) 800 °C, and (d) 1000 °C.

Fig. 2 EDS spectra of SiCN composite aerogels prepared by microwave heating at (a) 600 °C, (b) 800 °C, and (c) 1000 °C.

for the short whiskers, nanorods, and nanowires synthesized at 600, 800, and 1000 °C, respectively. The diameter of the individual 1D nanostructure is uniform along its length. The average lengths of the short whiskers, nanorods, and nanowires are several tens of nanometers, several hundreds of nanometers, and few micrometers, respectively, which indicated that the size of 1D nanostructure can be tailored by varying the temperatures of microwave heating.

Figure 3 shows the XRD patterns of SiCN aerogels and SiCN composite aerogels. We can see that the SiCN aerogels pyrolyzed at 1000 °C remain amorphous; however, the ferrocene-modified SiCN aerogels after microwave heating were in crystalline state, and the diffraction peaks at 35.6°, 41.4°, 60.0°, 71.8°, and 75.5° belong to the (111), (200), (220), (311), and (222) planes of β -SiC (JCPDS 29-1129), respectively. The low intensity peak marked with S.F. is due to stacking faults [22,23]. The diffraction peaks of sample mw-600 are broad in width and poor in intensity, suggesting low crystallization degree of SiC. With the microwave heating temperature increasing, the diffraction peaks of β -SiC become sharper in width and stronger in intensity. The increased intensity indicates the increasing crystallization degrees of SiC, and the decreased peak widths indicate the increase of the grain size. The peak at 26.1° was indexed as the (002) plane of graphite carbon (JCPDS 41-1487), and the peak at 45.3° was indexed as the (220) plane of Fe_3Si (JCPDS 45-1207), which correspond to the results of EDS spectra. Considering the PDC-SiCN begins to crystallize at 1400 °C [24,25], the above results indicate that the crystallization of PDC-SiCN can be effectively enhanced by the ferrocene catalyst-assisted microwave heating at lower temperatures. The decrease of crystallization

temperatures is due to the formation of liquid Fe-Si-C phase during microwave heating [26]. It is thought that the crystallization of SiC follows the solid-liquid-solid (SLS) mechanism when Fe exists in the system [27,28]. Precipitation occurs and gives rise to the SiC when the Fe-Si-C eutectic liquid alloys become saturated with Si and C atoms. Based on the above analysis, the 1D nanostructure in PDC-SiCN aerogels, according to their morphologies, is SiC whiskers, nanorods, or nanowires. Additionally, due to the oxygen distribution in SiCN matrix after ferrocene catalyst-assisted microwave heating, the SiCN composite aerogels after microwave heating were defined as SiC_{nw} -reinforced SiCNO ($\text{SiC}_{\text{nw}}/\text{SiCNO}$) composite aerogels.

Raman spectroscopy was employed to demonstrate the fine structure of carbon in PDCs. As shown in Fig. 4, all spectra exhibit the most prominent features of the disorder-induced D band at 1350 cm^{-1} and the G band at 1600 cm^{-1} caused by in-plane bond stretching of sp^2 carbons, suggesting the existence of free carbon in all samples. In addition, SiC band at about 800 cm^{-1} and 2D band at about 2700 cm^{-1} were presented in spectra of $\text{SiC}_{\text{nw}}/\text{SiCNO}$ composite aerogels. The 2D band is the overtone of the D band, which is sensitive to the stacking orders of graphene layers along the c axis [29]. In order to further analyze the features of free carbon, Raman spectra are fitted by the Lorentzian-BWF curve to determine the positions, widths, and $I_{\text{D}}/I_{\text{G}}$ intensity ratios (Table 1). Compared with the SiCN aerogels, the D band and G band of $\text{SiC}_{\text{nw}}/\text{SiCNO}$ composite aerogels increased in intensity and decreased in width, suggesting the increasing graphitization degree of carbon. With the increase of microwave heating temperatures, the D band, G band, and 2D band become sharper, indicating the increasing crystallization

Fig. 3 XRD patterns of SiCN aerogels and SiCN composite aerogels.

Fig. 4 Raman spectra of SiCN aerogels and $\text{SiC}_{\text{nw}}/\text{SiCNO}$ composite aerogels.

Table 1 Raman spectrum parameters of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels

Sample	no-mw	mw-600	mw-800	mw-1000
D peak (cm ⁻¹)	1334.46	1336.17	1337.30	1339.38
G peak (cm ⁻¹)	1593.96	1590.28	1586.69	1583.01
D peak FWHM (cm ⁻¹)	132.13	108.42	66.42	43.13
G peak FWHM (cm ⁻¹)	74.40	68.61	54.33	35.75
I_D/I_G	1.46	1.26	1.15	0.89

of carbon. Therefore, the microwave treatment and heating temperature both promoted the conversion of carbon from amorphous to graphite-like in SiC_{nw}/SiCNO composite aerogels.

Figure 5 shows the N₂ sorption isotherms and pore size distributions of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels. According to IUPAC classification, they are assigned to Type IV isotherms. The hysteresis loops could be further classified as H3, and the isotherm does not terminate at high pressure, indicating the presence of considerable fraction of mesopores and macropores. Hence, the PDC-SiCN aerogels consist of hierarchical porosity with a wide pore size dispersion in the range from 5 to 100 nm with a maximum close to 50 nm (Fig. 5(b)). It should be also mentioned that there is bimodal distribution in the pore diameter of 4 and 50 nm for the samples after microwave treatment. This can be explained that the smaller pore diameter is caused by the secondary SiC nanostructures and the larger pore diameter is caused by the primary SiCN frameworks. The details of pore size analysis are listed in Table 2. We can see that the PDC-SiCN aerogels have a surface area of 135 m²/g with average pore size of 18 nm. The BET surface areas of the SiC_{nw}/SiCNO composite aerogels were 165, 232, and 173 m²/g, which were higher than that of the SiCN aerogels.

Fig. 5 N₂ sorption isotherms and pore size distributions of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels.**Table 2 Microstructural features of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels**

Sample	BET surface area (m ² /g)	Pore volume (cm ³ /g)	Pore size (nm)
no-mw	135	0.44	18
mw-600	165	0.47	15
mw-800	232	0.49	12
mw-1000	173	0.40	12

Contrarily, the average pore size of the SiC_{nw}/SiCNO composite aerogels was lower than that of the SiCN aerogel, which are 15, 12, and 12 nm. As the temperature of microwave treatment increased up to 1000 °C, the BET surface areas of the SiC_{nw}/SiCNO composite aerogels decrease, which is attribute to the formation of many 1D SiC nanostructures from SiCN matrix, leading to the collapse of partial frameworks and the increase of average pore size.

The TEM images of PDC-SiCN aerogels and SiC_{nw}/SiCNO composite aerogels are presented in Fig. 6. From Figs. 6(a)–6(c) we can see that the SiCN aerogels contain SiCN matrix and free carbon, and the selected area electric diffraction (SAED) inset in Fig. 6(a) shows a diffuse elastically scattered ring pattern, indicating the typical amorphous feature. As is seen from Figs. 6(e) and 6(f), the SiC nanowires with a diameter of about 30 nm can be observed clearly, associating with SiCN matrix and flexible graphene-like carbon. The interface spacing of 0.252 nm presented in TEM image (Fig. 6(d)) belongs to (111) plane of β-SiC. The corresponding SAED pattern indicates the existence of stacking faults, which originate from the environmental disturbances. The diffraction spots and rings also belong to the diffractions of SiC.

The synthesis mechanism of SiC_{nw}/SiCNO composite aerogels occurred in high-energy microwave irradiation was discussed in detail, and the schematic is shown in Fig. 7. In the process of microwave treatment, free carbon within SiCN aerogels possess strong microwave absorbing ability, which can achieve selective and effective heating by the coupled thermal effect [30,31]. Firstly, under the action of microwave alternating electric field, the π electrons of free carbon can move in the local state to form current; moreover, the π electrons induced by microwave alternating electric field cannot be synchronized with the rapidly changes of electric field, so the electromagnetic energy will be converted into thermal energy, realizing the microwave heating. Then, ferrocenes loaded on the surfaces of

Fig. 6 TEM and SAED images of (a–c) SiCN aerogels and (d–f) SiC_{nw}/SiCNO composite aerogels prepared by microwave heating at 1000 °C.

Fig. 7 Formation mechanism of 1D SiC in SiC_{nw}/SiCNO composite aerogels.

SiCN aerogels begun to thermally decompose at about 200 °C by the heat from microwave absorbing of free carbons. The thermal decomposition products of ferrocenes were Fe nanoclusters and cyclopentadienyl, which are used as catalyst and partial carbon source, respectively. Under the Fe catalyst-assisted microwave heating, Si and C atoms were separated out to form SiC nucleation on the surfaces of SiCN matrix in the early stage; subsequently, 1D SiC nanostructures were grown on the surfaces or void spaces of SiCN matrix via an SLS mechanism [27]. The 3D porous structure

of SiCN aerogels can provide sufficient space for the growth of SiC nanostructures, which can act as dielectric loss phases and interact with the microwave, further promoting the growth of 1D SiC nanostructures.

3.2 Microwave absorption property of SiC_{nw}/SiCNO composite aerogels

The relative complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$), permeability ($\mu_r = \mu' - j\mu''$), dielectric loss tangent, and magnetic loss tangent of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels are presented in Fig. 8. It was

Fig. 8 (a, b) permittivity, (c) dielectric loss tangent, (d, e) permeability, and (f) magnetic loss tangent of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels.

found that, in comparison to the SiCN aerogels, the real (ϵ') and imaginary (ϵ'') parts of complex permittivity, as well as the dielectric loss tangent ($\tan\delta_\epsilon = \epsilon''/\epsilon'$) of SiC_{nw}/SiCNO composite aerogels obviously increased. It is well-known that ϵ' represents the storage capability of electric energy and ϵ'' represents the loss capability of electric energy, which are the key parameters for the characterization of dielectric property and predicting their EMA property. The significant changes in permittivity are mainly attributed to the 1D SiC nanostructures and graphite-like carbon, which improved the interfacial polarization. Owing to the enhanced electric conductivity resulted from the graphitization of free carbon through sp^3 to sp^2 transition by microwave treatment, the dielectric loss increased with the microwave heating temperatures [17]. Therefore, the ϵ' and ϵ'' of SiC_{nw}/SiCNO composite aerogels can be effectively tailored by microwave treatment. However, the enhanced oxidation at 1000 °C resulted in the ϵ' and ϵ'' of the SiC_{nw}/SiCNO composite aerogels

microwave-treated at 1000 °C lower than that of the other samples microwave-treated at 600 and 800 °C. The variations of real (μ') and imaginary (μ'') parts of complex permeability, as well as the magnetic loss tangent ($\tan\delta_\mu = \mu''/\mu'$) of SiC_{nw}/SiCNO composite aerogels are smaller due to the trace generation of Fe₃Si, indicating minor magnetic loss contributions.

Figure 9 shows the reflection loss (RL) of SiCN aerogels and SiC_{nw}/SiCNO composite aerogels with 88 wt% paraffin wax. The RL can be calculated according to Eqs. (1) and (2) based on the measured ϵ_r and μ_r [32,33]:

$$RL = 20 \log |(Z_{in} - Z_0) / (Z_{in} + Z_0)| \quad (1)$$

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

where Z_0 is the impedance of free space, Z_{in} is the input characteristic impedance, ϵ_r is the complex permittivity, μ_r is the complex permeability, f is the frequency, c is the velocity of light, and d is the thickness of materials.

Fig. 9 RL of (a) SiCN aerogels and SiCN_{nw}/SiCNO composite aerogels prepared by microwave heating at (b) 600 °C, (c) 800 °C, and (d) 1000 °C.

As shown in Fig. 9, it was found that the EMA property of SiCN_{nw}/SiCNO composite aerogels after microwave heating was significantly higher than the SiCN aerogels. The minimum RL of mw-600, mw-800, and mw-1000 are −23.9 dB@13.8 GHz, −26.5 dB @10.9 GHz, and −20.4 dB@14.5 GHz with the effective bandwidth of 5.2 GHz, 3.2 GHz, and 4.8 GHz at 2.0 mm thickness, respectively. Moreover, the minimum RL of mw-800 can reach to −31.9 dB at 3.0 mm thickness. The heterogeneous structure in SiCN_{nw}/SiCNO composite aerogels can cause multiple scattering and interface polarization, which is conducive to enhance the dielectric loss and improve the EMA properties [34].

According to Debye theory, the dielectric loss consists of polarization loss and conductivity loss. The Debye relaxation equations are as follows [35,36]:

$$\left(\varepsilon' - \frac{\varepsilon_s + \varepsilon_\infty}{2} \right)^2 + (\varepsilon'')^2 = \left(\frac{\varepsilon_s - \varepsilon_\infty}{2} \right)^2 \quad (3)$$

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2 \tau^2} \quad (4)$$

$$\varepsilon'' = \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2 \tau^2} \omega \tau + \frac{\sigma}{\omega \varepsilon_0} \quad (5)$$

where ε_s is the static permittivity and ε_∞ is the permittivity at infinite frequency. Obeying these equations, ε' and ε'' may form a semicircular curve called Cole–Cole semicircle. Each semicircle corresponds

to one Debye relaxation process [37]. In order to clarify the origin of the relaxation processes, the plots of ε' versus ε'' of SiCN aerogels and SiCN_{nw}/SiCNO composite aerogels were curved and shown in Fig. 10. It can be seen that there are some multi-dielectric relaxation processes in SiCN aerogels; however, compared with SiCN aerogels, the composite aerogels possess more additional semicircles, and the widths of semicircles are also larger, indicating that the presence of 1D SiC nanostructures increases the number of relaxation processes and improves the intensity of the Debye relaxation processes. This behavior may be related to the charge transfer process occurring at the interfaces between SiC nanostructures and amorphous SiCN matrix. In addition, it should be noticed that there is also hopping migration between neighboring graphite-like carbon in the composite aerogels. The improved dielectric relaxation processes are also reflected in the tangent loss of SiCN_{nw}/SiCNO composite aerogels and SiCN aerogels, as shown in Fig. 8(c). It can be found that the tangent loss of composite aerogels is higher than that of the SiCN aerogels over 2–18 GHz.

The schematic illustration of the microwave absorption mechanism in SiCN_{nw}/SiCNO composite aerogels was shown in Fig. 11. The superior EMA properties of the composite aerogels are mainly attributed to the improved impedance matching due to the “antenna

Fig. 10 Cole–Cole plots of (a) SiCN aerogels and SiC_{nw}/SiCNO composite aerogels prepared by microwave heating at (b) 600 °C, (c) 800 °C, and (d) 1000 °C.

Fig. 11 Schematic illustration of the microwave absorption mechanism in SiC_{nw}/SiCNO composite aerogels.

effect” caused by 1D SiC_{nw} and proper electric conductivity, as well as the EM attenuation ability resulted from multi-interfacial polarization (free carbon, SiCNO, and SiC_{nw}), multi-reflection, and micro current caused by migration of hopping electrons.

4 Conclusions

In summary, 1D SiC nanostructures were grown in-situ on the surfaces or void spaces in PDC-SiCN aerogels by catalyst-assisted microwave heating approach at ultra-low temperature. The formation process of 1D SiC nanostructures is ascribed to the SLS mechanism and the microwave couple effect. The minimum RL of SiC_{nw}/SiCNO composite aerogels (mw-600, mw-800, and mw-1000) are −23.9 dB@13.8 GHz, −26.5 dB

@10.9 GHz, and −20.4 dB@14.5 GHz with the effective bandwidth of 5.2 GHz, 3.2 GHz, and 4.8 GHz at 2.0 mm thickness, respectively. Experimental results and the theoretical simulation indicate that the enhanced EMA property of SiC_{nw}/SiCNO composite aerogels is attributed to the special structural characteristics, the improved impedance matching, interfacial polarization, multi-reflection, and micro current caused by migration of hopping electrons. In conclusion, this study provides an effective modification approach to improve the EMA property of PDC-SiCN aerogels, and the SiC_{nw}/SiCNO composite aerogels could be considered as a promising candidate in light-weight EMA materials.

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