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Enhanced microwave absorption properties of graphite nanoflakes by coating hexagonal boron nitride nanocrystals

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Graphical abstract

HIGHLIGHTS

- Hexagonal boron nitride nanocrystal/graphite nanoflakes (*h*-BNNC/GNFs) are prepared.
- These *h*-BNNC/GNFs are fabricated *via* a facile *in-situ* thermal treatment process.
- *h*-BNNCs are highly crystallized and anchored on the surface of graphite nanoflakes.
- These *h*-BNNC/GNFs exhibit excellent microwave absorption properties.

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ABSTRACT

We report herein the synthesis of a novel hexagonal boron nitride nanocrystal/graphite nanoflake (*h*-BNNC/GNF) composite through a wet-chemistry coating of graphite nanoflakes and subsequent *in-situ* thermal treatment process. The characterization results of X-ray diffraction, scanning electron microscope, transmission electron microscope, energy dispersive X-ray spectrum, and X-ray photoelectron spectroscopy demonstrate that *h*-BNNCs with diameter of tens of nanometers are highly crystallized and anchored on the surfaces of graphite nanoflakes without obvious aggregation. The minimum reflection loss (RL) value of the *h*-BNNC/GNF based absorbers could reach -32.38 dB ($> 99.99\%$ attenuation) with the absorber thickness of 2.0 mm. This result is superior to the other graphite based and some dielectric loss microwave absorption materials recently reported. Moreover, the frequency range where the RL is less than -10 dB is 3.49-17.28 GHz with the corresponding thickness of 5.0 to 1.5 mm. This reveals a better electromagnetic microwave absorption performance of *h*-BNNC/GNFs from the X-band to the K_u-band. The remarkable enhancement of the electromagnetic microwave absorption properties of *h*-BNNC/GNFs can be assigned to the increase of multiple scattering, interface polarization as well as the improvement of the electromagnetic impedance matching of graphite nanoflakes after being coated with *h*-BNNCs.

Keywords: hexagonal boron nitride nanocrystals, graphite nanoflakes, composite, electromagnetic microwave, absorption property

1. Introduction

Electromagnetic microwave absorption materials have gained increasing attention due to the high demand for effective reduction of the electromagnetic radiation and improvement of anti-electromagnetic interference from industrial to military fields [1-5]. In the past decades, an overwhelming research on the novel electromagnetic microwave absorption (MA) materials has been made [1-28]. Dielectric and magnetic materials are currently two main types of materials that are used as electromagnetic MA materials [29]. The electromagnetic microwave absorbing properties of such materials are determined by their dielectric properties (the complex permittivity; $\epsilon_r = \epsilon' - j\epsilon''$), magnetic properties (the complex permeability;

$\mu_r = \mu' - j\mu''$), electromagnetic impedance matching as well as the thickness of the absorbers [1, 5, 29-32]. However, there are some other shortcomings restricting their practical applications. For example, the dielectric absorption materials exhibit narrow absorbing frequency bandwidth while the magnetic absorption materials possess high density that cannot be used in large quantity as fillers of absorbers [33]. As a result, for many civil and military applications, research is still focused on developing novel electromagnetic MA materials with thin thickness, low density, high thermal stability, and absorption over broad electromagnetic frequency bandwidth [5, 30, 34].

Comparing with magnetic loss absorption materials, the electrical loss absorption material have become one kind of the most preferred absorption materials due to their relatively low density [29]. Among them, carbonaceous materials are the typical electrical loss absorption materials, because these materials possess relatively low density, tunable properties, abundant resources, simple preparation process, and low cost [29], *etc.*. Graphite flakes, a kind of typical carbonaceous materials, have attracted considerable attention owing to their unique properties, such as low density, good chemical inertness, excellent mechanical performance, high oxidation resistance, outstanding electrical conductivity as well as the sufficient dielectric loss property [25]. Moreover, the graphite flakes are present in abundance naturally. Therefore, graphite flakes are considered as ideal electromagnetic MA materials. However, large dielectric loss of graphite flakes often results in the unexpected reflection of microwaves. Hence, it is of great necessity for graphite flakes to combine with other materials to improve their electromagnetic microwave absorbing properties. Currently, the main research focuses on the modification or decoration of graphite flakes, which produces graphite oxide or nano-graphite and thus form high performance graphite based absorbing materials [29, 35-40].

Hexagonal boron nitride (*h*-BN) composed of sp^2 bonded boron and nitride atoms, is structurally analogous to carbon materials with almost the same crystal lattice parameters [41]. Moreover, *h*-BN possesses larger electrical resistivity and cannot influence the attenuating electromagnetic wave energy of graphite. These unique properties combining with the remarkable mechanical properties, high chemical inertness and thermal stability, excellent resistance to oxidation make *h*-BN an excellent alternative

candidate for producing ideal electromagnetic MA composites with graphite flakes. Therefore, in current report, we have selected nonmagnetic *h*-BN nanocrystals which differ from the conventional magnetic and dielectric phases to adjust the electromagnetic parameters of graphite flakes. These special *h*-BN nanocrystal/graphite nanoflake (*h*-BNNC/GNF) composite is fabricated through a facile wet-chemistry coating and subsequent *in-situ* thermal treatment process. The composition and structure of this novel *h*-BNNC/GNF composite are confirmed by X-ray diffraction (XRD), scanning electron microscope (SEM), transmission electron microscope (TEM), energy dispersive X-ray spectroscopy (EDX) and X-ray photoelectron spectroscopy (XPS). The microwave absorbing properties of *h*-BNNC/GNF based absorbers with different thicknesses are systemically investigated in the frequency range of 2-18 GHz. Noticeable enhancement of MA property is achieved after coating *h*-BNNCs on the surfaces of graphite nanoflakes. Finally, the mechanism for the enhanced MA properties of these *h*-BNNC/GNFs has also been studied in detail.

2. Experimental

2.1. Materials

Ammonia borane used in this work was synthesized according to the literature [42] using sodium borohydride and ammonium formate as starting materials. Graphite nanoflakes with average diameter of 500 nm were purchased from Dongguan Jiecheng graphite Co., Ltd. All other reagents were of analytical grade, and provided from Tianjin Kermel Chemical Reagent Co. Ltd. (Tianjin, China), and used without further purification.

2.2. Preparation of *h*-BNNC/GNFs

The synthesis of *h*-BNNC/GNFs has been carried out *via* a wet-chemistry coating and subsequent thermal treatment process as shown in Fig. 1. In a typical procedure, ammonia borane was first dissolved in 1, 4-dioxane to form a clear solution with a concentration of 0.1 mol/L. Secondly, 0.1 g natural graphite nanoflakes were dispersed into the solution by ultrasonication.

Then, the as-obtained slurry was maintained at a temperature of 95 °C for 24 h under mechanical stirring followed by the evaporation of 1, 4-dioxane at the same temperature. Finally, the powder collected by filtration and following vacuum drying process were further calcined in a tubular furnace at 1400 °C for 60 min under the protection of high purity argon (100 sccm) to achieve the crystal conversion.

2.3. Structure characterization

XRD spectrum of the as-obtained sample was recorded using Rigaku X-ray diffractometer with Cu K α radiation, and the diffraction points were recorded from 10° to 80°. The structure of the as-obtained sample was characterized by SEM (TESCAN VEGA II) and TEM (JEM-2100, equipped with EDX system). XPS (Kratos Axis Ultra DLD) operating at 10 mA and 15 kV was utilized to investigate the elemental composition and surface chemical bonds of the as-obtained sample.

2.4. Electromagnetic parameter measurements

To evaluate the MA performance of the samples (natural graphite nanoflakes and *h*-BNNC/GNFs), composite samples were prepared by firstly mixing the sample powders and paraffin wax with mass ratios of 2:3. Then the mixtures were pressed into toroidal shaped rings with inner diameter of 3 mm, outer diameter of 7 mm, and thickness of 3 mm. The electromagnetic parameters of the composites were measured on a vector network analyzer (VNA; Agilent N5245A) in transmission/reflection mode in the range of 2-18 GHz. The power level of the incident microwave radiation used for the measurements is -15 dBm. The electromagnetic parameters of the samples were calculated via HP85071 software.

3. Results and discussion

3.1. Characterization of *h*-BNNC/GNFs

Fig. 2 shows the SEM images of original natural graphite nanoflakes and the as-obtained composites. A uniform lamellar graphite nanoflakes with lateral size of about 3 μ m and thickness

of tens of nanometers can be clearly observed in Fig. 2a and b. After being coated with *h*-BNNCs, the lamellar morphology of graphite nanoflakes still remains, and no obvious aggregation is observed (Fig. 2c). In the magnified SEM image (Fig. 2d), a large number of nanoparticles (as marked by red arrows) distributing on the surfaces of graphite nanoflakes can be seen clearly. This suggests that the as-expected nanoparticles are successfully anchored onto the surfaces of graphite nanoflakes.

The crystal structure of the as-obtained samples is characterized by XRD. As shown in Fig. 3a, the diffraction peaks around $2\theta = 26^\circ$ can be attributed to the (002) planes of graphite (JCPDS card No.41-1487) and *h*-BN (JCPDS card No. 34-0421). It is noteworthy that the lattice constants of *h*-BN ($a_0 = b_0 = 2.50 - 2.51 \text{ \AA}$, $c_0 = 6.66 - 6.67 \text{ \AA}$) are almost the same as those of graphite ($a_0 = 2.5 \text{ \AA}$ and $c_0 = 6.7 \text{ \AA}$) [41]. Besides graphite, it is reasonable to speculate that the weak peak of (002) phase of *h*-BN is covered by the strong graphite peak and is not visible. However, the intensity of the peaks centered at about $2\theta = 44^\circ$ is similar and they can be identified in magnified peaks as shown in Fig. 3b. The peak centered at $2\theta = 44.1^\circ$ can be assigned to the (100) phase of *h*-BN while the other peak centered at $2\theta = 44.7^\circ$ originates from (100) phase of graphite. To further clarify the detailed crystal structure of the as-obtained samples, TEM analysis is employed. Fig. 4a presents a low magnification TEM image of a single as-obtained nanoflake. This TEM image shows that numerous nanoparticles are anchored on the surface of graphite nanoflake, which is in accordance with the SEM analysis. The selected area electron diffraction (SAED) pattern taken from the nanoflake is shown in Fig. 4b. Sharp scattered diffraction spots arise from the graphite nanoflakes, while the diffraction rings can be ascribed to the polycrystalline *h*-BNNCs. The size of the coated nanoparticles is uniform with a diameter of about 20 nm as shown in Fig. 4c. The HRTEM image (Fig. 4d) demonstrates the high crystallinity of the anchored nanoparticles in which

parallel lattice fringes can be observed clearly. The average spacing between adjacent fringes is calculated to about 0.34 nm (inset in Fig. 4d), which is typical for (002) plane of *h*-BN.

The chemical composition of the as-obtained products is analyzed using EDX spectroscopy, as presented in Fig. 5. Pronounced signals of N and C are detected which originate from the anchored *h*-BNNCs and graphite nanoflakes, respectively. B element is not detected in the EDX analysis due to the detection limitation of the apparatus. The elemental mappings of N and C (insets of (b) and (c) in Fig. 5) obtained from the corresponding TEM image inserted in Fig. 5a, further demonstrate that *h*-BNNCs are homogeneously distributed on the surface of graphite nanoflakes. Due to the detection limitation of the EDX analysis, further elemental characterization of the *h*-BNNC/GNFs is performed using XPS analysis. Clearly, the as-obtained composite comprised of B, C, N and O elements as shown in survey XPS spectrum (Fig. 6a). Fig. 6b shows the B_{1s} fine spectrum of the as-obtained sample which is fitted into two peaks at 190.8 and 193.1 eV, respectively. The main peak centered at 190.8 eV can be assigned to *h*-BN nanocrystals which is the same as the value reported for B_{1s} in *h*-BN nanosheets synthesized by the CVD method [43]. The other one centered at 193.1 eV results from B-O bond which is due to the contamination of B₂O₃ and exposure of the sample to air [44, 45]. In addition, the N_{1s} peak can also be fitted into two peaks as shown in Fig. 6c. This peak with binding energy of 398.1 eV can be assigned to N-B covalent bond in *h*-BN [44, 46-48], corresponding to the B-N bond in B_{1s} zone. The other peak with binding energy of 398.9 eV corresponds to N bonded to both C and B (B-N-C) [49], indicating that some nitrogen has reacted with graphite during the thermal treatment process. Based on the intensity and energy of the major peaks in B_{1s} and N_{1s} spectra, it can be concluded that B and N are mainly bonded as B-N, which strongly implies the existence of BN phase in the as-obtained sample [50].

3.2. Microwave absorption properties of *h*-BNNC/GNFs

The microwave absorbing properties of MA materials are closely associated with their relative complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and complex permeability ($\mu_r = \mu' - j\mu''$). Real permittivity (ϵ') and real permeability (μ') represent the storage ability related to electric and magnetic energy, while the imaginary permittivity (ϵ'') and imaginary permeability (μ'') are in regards to the dissipation of electric and magnetic energy [1, 5, 31, 32]. The complex permittivity of the as-obtained *h*-BNNC/GNFs and graphite nanoflakes has been evaluated on the basis of the transmission line theory [10]. It is notable that the complex permeability ($\mu_r = \mu' - j\mu''$) of the as-obtained *h*-BNNC/GNFs is not shown because the samples have no magnetic properties. In addition, the corresponding parameters of the natural graphite nanoflakes have also been studied for comparison. Fig. 7 illustrates the electromagnetic performances of graphite nanoflake and the as-obtained *h*-BNNC/GNF based absorbers at room temperature in the frequency range of 2-18 GHz. Fig. 7a and b show the complex permittivity of original graphite nanoflake and *h*-BNNC/GNF based absorbers, respectively. Within the frequency range of 2-18 GHz, the curve variation tendency of graphite nanoflake based absorber is similar with that of *h*-BNNC/GNF based one. Nevertheless, the values of ϵ' and ϵ'' for original graphite nanoflakes are higher than those of *h*-BNNC/GNFs, which could be attributed to the introduction of *h*-BNNCs on the surfaces of graphite nanoflakes. Fig. 7c exhibits the dielectric tangent loss of the original graphite nanoflake and *h*-BNNC/GNF based absorbers, respectively. Generally, the dielectric tangent loss ($\tan\delta_\epsilon = \epsilon''/\epsilon'$) is commonly used to describe MA [22]. It is observed that the values of $\tan\delta_\epsilon$ for *h*-BNNC/GNF based absorbers are smaller than those of graphite nanoflake based absorbers in the measured frequency range of 2-18 GHz. It is observed that the values of both $\tan\delta_\epsilon$ decrease in 5-18 GHz after *h*-BNNC coating. It is speculated that the

shrinking gap of dielectric tangent loss results from the *h*-BNNC coating. According to the principle of impedance matching, the values of dielectric tangent loss need to be approximately equal to the magnetic tangent loss. As a kind of typical electronic material, the dielectric tangent loss of graphite nanoflakes is much larger than magnetic tangent loss. Correspondingly, the tremendous gap leads to excessive reflection of microwave.

To compare the microwave absorption properties between original graphite nanoflakes and *h*-BNNC/GNFs, the reflection loss values are calculated using the measured complex permeability and permittivity at 2-18 GHz with a sample thickness of 3 mm according to the transmit line theory as follows:

$$RL(dB) = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad \langle \text{InlineImage18} \rangle$$

Where the normalized input impedance (Z_{in}) is given by the formula:

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c} \right) \sqrt{\mu_r \epsilon_r} \right] \quad \langle \text{InlineImage19} \rangle$$

where f is the electromagnetic microwave frequency, d , c , Z_{in} $\langle \text{InlineImage20} \rangle$ and Z_0 are the sample thickness, the velocity of light, the input impedance of absorber and the impedance of free space, respectively [51]. Fig. 8 shows the RL for original graphite nanoflake and the *h*-BNNC/GNF based absorbers with different thicknesses in the frequency range of 2-18 GHz, respectively. As observed in Fig. 8a, with the increase of sample thickness, the absorbing frequency moved to lower frequency, suggesting that the range of absorption frequency can be tuned by adjusting the thickness of the absorbers. The RL of the original graphite nanoflake based absorber is relatively poor and all the minimum RL values are less than -10 dB within the thicknesses of 1-5 mm. For the *h*-BNNC/GNF based absorber, the RL performance is tremendously improved as summarized in Table 1. The maximum RL value can reach -32.38 dB at 11.20

GHz with a thickness of 2.0 mm, and the RL below -10 dB is in the frequency range between 9.70 and 12.98 GHz. In addition, the widest frequency range where RL is lower than -10 dB is 13.40-17.28 GHz when the thickness of the absorber decreases to 1.5 mm. Moreover, the frequency range where RL is lower than -10 dB is 3.49-17.28 GHz with a corresponding thickness of 5.0 to 1.5 mm, revealing that the *h*-BNNC/GNF based absorbers have superior electromagnetic microwave absorption performance from the X-band to the K_u-band [31]. Usually, a material with a RL value less than -30 dB is regarded as an excellent absorber as this value corresponds to 99.999% reflection loss or absorption [52]. Therefore, compared with original graphite nanoflakes, *h*-BNNC/GNFs not only have larger values of RL but also possess broader bandwidth. It is clear from Table 2 that the as-obtained *h*-BNNC/GNFs exhibit an excellent ability to absorb electromagnetic microwave in comparison to the representative graphite and some other dielectric loss material based composites.

Table 1 The electromagnetic microwave absorption properties of *h*-BNNC/GNF based absorbers with different thickness.

Thickness (mm)	Absorbing peak (GHz)	RL (dB)	Absorption bandwidth (GHz, <-10 dB)
1.5	15.12	-23.50	3.86
2.0	11.20	-32.38	3.28
2.5	8.64	-26.18	2.48
3.0	6.96	-20.54	2.08
3.5	5.84	-19.03	1.60
4.0	5.04	-17.80	1.36
4.5	4.40	-17.06	1.20
5.0	3.92	-16.06	1.04

The enhancement of the MA performance of *h*-BNNC/GNFs is mainly attributed to a number of factors. Generally, higher dielectric loss is favorable for higher MA. In current case, the graphite nanoflakes with stronger dielectric loss fail to produce considerable RL, because there are another three important parameters benefitting the RL of these novel *h*-BNNC/GNFs. The first one is the impedance matching. It will reduce the reflection of microwaves at the front surface of the MA materials when the characteristic impedance of the MA materials is equal/close to that of the free space [61, 62]. The impedance matching

of a MA material is related to the relationship between the complex permittivity and complex permeability. Most of the incident electromagnetic waves will be reflected off by the MA materials because of the low surface resistance caused by the large gap between the complex permittivity and the complex permeability [63]. For graphite nanoflakes, the gap between its complex permittivity and complex permeability is too large, thus effective MA is hindered by its poor impedance matching. In contrast, the gap between complex permittivity and complex permeability of *h*-BNNC/GNFs is much smaller, which will result in a better impedance matching. Fig. 9 shows the Z (Z_{in}/Z_0) values for *h*-BNNC/GNF based absorbers with different thickness. For the layer of 2 mm, the maximum RL of -32.38 dB can be obtained at 11.20 GHz when the Z value is close to 1, revealing the important role of the impedance matching [64-66]. More microwaves will transmit into the absorbers when the Z value is close to 1, and this will result in better MA properties. The second parameter is the multiple reflections of the microwaves. The microwave propagation path in the *h*-BNNC/GNF based absorbers extends which increases the reflection of the microwaves. The TEM images show that the *h*-BNNCs randomly distribute on the surfaces of graphite nanoflakes, and this can be simplified as the islanding model where each *h*-BNNC can be regarded as an isolated island [29]. As a result, the reflection loss of microwave occurs not only among plenty of graphite nanoflakes in the absorber but also within these *h*-BNNC islands. These *h*-BNNC islands can effectively increase the frequency of multiple reflections, which corresponds to the extension of microwave propagation paths, thus enhancing the scattering loss of microwaves. Finally, the enhancement of the microwave absorption performances of *h*-BNNC/GNFs could be caused by the increase of the interfacial polarization and charge accumulations caused by the built-in electrical field along the boundaries between *h*-BNNCs and graphite nanoflakes [52]. The crystal planes along the interface are different even if the crystalline phases are similar, and this will cause disorder/crystalline interfaces [67, 68]. Therefore, defects and dangling bonds are commonly formed along the interfaces for charge accumulation [69]. In addition, different crystal planes will have different electronic structures, such as different conduction and valence band positions, which will result in a mismatch between the electronic structures of the crystalline planes along the interfaces. As a result, charge

imbalance and redistribution along the interface are caused, thus introduce a polarization effect and the built-in internal electrical field along the interfaces [70]. Moreover, the polarization will be stronger when the interfacial area is higher or near the interface or surface [52]. Therefore, the enhancement of the MA properties *h*-BNNC/GNFs can be assigned to the improvement of the electromagnetic impedance matching, increase of multiple scattering and interface polarization of graphite nanoflakes after being coated with *h*-BNNCs.

Table 2 Comparison of Electromagnetic Microwave Absorption Properties of *h*-BNNC/GNF Based Absorbers with Those of Other Graphite and Dielectric Loss Material Based Absorbers Recently Reported

Materials	RL (dB)	Thickness (mm)	Absorption bandwidth (<-10dB) (GHz,	Content (%)	Reference
Microcrystalline graphite	-18.24	2-2.1	~1.7	60	[29]
Mechanical milled graphite	-25.5	2	~2.8	30	[35]
Graphite/novolac phenolic resin composite	> -17	3.7	-13 to -17 (8-13GHz)	30	[36]
FeCo particles coated graphite nanoflake	-30.6	2	~1.8	30	[38]
Nickel/graphite	> -9	2	-	100	[39]
Polypyrrole/Nickel/graphite	-23.46	2	4.2 (< -15dB)	100	[39]
Silver/graphite	~ -14	2	~5 (< -13dB)	100	[40]
Polypyrrole/Silver/graphite	-18.21	2	4.2 (< -15dB)	100	[40]
Hydrogenated BaTiO ₃ nanoparticles	-36.9	2	~2	60	[52]
BaTiO ₃ nanoparticles	-21.8	2	1.7	70	[53]
BFTO/MCNTs/P3MT composites	-21.56	2	3.25	33.3	[54]
Nb/Al ₂ O ₃ composite	-27.3	1.5	1.8	100	[55]
Al doped ZnO/ZnSrO ₄	-32.0	3.5	4.2	100	[56]
SiC microtubes	-23.9	1.0	2	20	[57]
SiC nanowires reinforced SiOC ceramics	-20.01	3.3	3.57	100	[58]
SiC nanowires	-17.4	3.0	2.5	30	[59]
Stacking fault SiC nanowires	-30.0	4.6	3.7	50	[60]
Graphite flakes	~ -10	1.5	-	40	This work
<i>h</i> -BNNC/GNFs	-32.38	2	3.28	40	This work
<i>h</i> -BNNC/GNFs	-23.54	1.5	3.86	40	This work

4. Conclusions

In summary, a new method to fabricate *h*-BNNC/GNFs with greatly improved MA property has been established, which involves a facile wet-chemistry coating and subsequent thermal treatment step. In the as-obtained *h*-BNNC/GNFs, *h*-BNNCs with diameter of tens of nanometers are highly crystallized and anchored on the surface of graphite nanoflakes. The RL value shows that the minimum reflection loss of the *h*-BNNC/GNF materials is about -32.38 dB at 11.20 GHz with a thickness of 2.0 mm, and the widest absorption bandwidth (< -10 dB) is 3.86 GHz when the materials thickness drops to 1.5 mm. Moreover, the RL values bellow -10 dB is in the frequency range of 3.49 to 17.28 GHz with a corresponding thickness of 5.0 to 1.5 mm, showing a superior electromagnetic MA performance of *h*-BNNC/GNFs from the X-band to the Ku-band. The remarkable enhanced electromagnetic MA properties of the *h*-BNNC/GNFs is due to the increase of multiple scattering, interface polarization and the improved impedance matching of graphite nanoflakes coated with *h*-BNNCs. The *h*-BNNC/GNFs with low density, small thickness and strong absorption are of potential as electromagnetic microwave absorbing materials.

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<InlineImage2>

Fig. 1. Schematic illustration of the fabrication process of *h*-BNNC/GNFs.

<InlineImage3>

Fig. 2. SEM images of (a, b) original graphite nanoflakes, and (c, d) as-obtained *h*-BNNC/GNFs.

Fig. 3. The XRD patterns of the as-obtained *h*-BNNC/GNFs in the range of (a) 10-80° and (b) 42-47°, respectively.

<InlineImage6>

Fig. 4. (a) Typical low magnification TEM image, (b) SAED pattern, (c-d) high-magnification TEM images of the as-obtained products. Inset in d: measurement of the lattice fringes showing interplanar spacing.

Fig. 5. EDX spectrum collected from the representative *h*-BNNC/GNFs. Insets: the TEM image and corresponding elemental mappings of N and C.

Fig. 6. (a) Survey, (b) fitted B_{1s} and (c) fitted N_{1s} XPS spectra recorded from the h -BNNC/GNFs.

<InlineImage15>

Fig. 7. Frequency dependence of the real parts (a) and imaginary parts (b) of relative complex dielectric permittivity, and the corresponding dielectric loss (c) for GNFs and *h*-BNNC/GNFs, respectively.

<InlineImage17>

Fig. 8. Frequency dependences of RL for (a) original graphite nanoflake, and (b) *h*-BNNC/GNF based absorbers with different thickness.

Fig. 9 The relationship between Z_{in}/Z_0 of h -BNNC/GNF based absorbers with different thicknesses.