Supplementary Information

Core-shell Si_3N_4@WS_2 porous ceramics with improved electromagnetic wave absorption performance

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Preparation of porous Si_3N_4 ceramics

A mixture of Si_3N_4 powder, mono-dispersed poly methyl methacrylate (PMMA, d_{50}=~50 μm), and Lu_2O_3, (Si_3N_4:PMMA:Lu_2O_3 = 67.2:30:2.8) was wet-milled for 4 h by a planetary ball milling at 300 rpm using Si_3N_4 balls as the milling media and ethanol as a liquid medium to obtain mixture slurry. The mass ratio for powder mixture:Si_3N_4 balls:liquid medium was 1:2:1. After drying at 70 °C for 24 h, the uniformly-mixed powders were uniaxially pressed into a square die using a uniaxial compactor machine under the 20 MPa to obtain green bodies. The green bodies were heated at 600 ℃ for 2 h in the air to remove the PMMA by oxidation, and then sintered at 1670 °C for 3 h in a 0.3 MPa nitrogen atmosphere.

Characterization:

The phase composition of the samples was analyzed via X-ray diffraction (XRD, Cu Kα as radiation, Germany). The morphology of the fracture surface was observed using field emission scanning electron microscope (SEM, Hitachi SU8220, Japan) and transmission electron microscopy (TEM, JEM-2100F). Apparent porosity was measured by the Archimedes method. Raman spectra were obtained on a LabRam HR800 with a visible laser (532 nm) to characterize the structure of the samples. The vector network analyzer (VNA, Agilent E5071C; China) was carried out to test the complex permittivity of the samples with dimensions of 22.86 mm × 10.16 mm × 3 mm in the frequency range of 8.2-12.4 GHz

Electromagnetic Formulas:

The complex permittivity ($\varepsilon_r = \varepsilon^{'} - j\varepsilon^{''}$) and complex permeability ($\mu_r = \mu^{'} - j\mu^{''}$)

were tested using the wave-guide method. The ε' and μ' values represent the capacity to store electromagnetic energy, while ε'' and μ'' represent the inner dissipation. Based on transmission line theory, the reflection loss (RL) was calculated using ε_r and μ_r as following equations:

$$RL = 20\log_{10}\frac{|Z_{in} - Z_0|}{|Z_{in} + Z_0|} \quad (1)$$

$$Z_{in} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}tanh[j\frac{2\pi fd}{c}\sqrt{\mu_r\varepsilon_r}] \quad (2)$$

where Z_{in} is the input impedance of the microwave absorber layer, Z_0 is the impedance of the EMW in free space. *c*, *f*, and *d* are the light speed, frequency, and matching thickness of the absorber, respectively.

The attenuation constant (α) can be calculated through:

$$\alpha = \frac{\sqrt{2}\pi f}{c}[(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon')^2 + (\mu'\varepsilon'' + \mu''\varepsilon')^2}]^{\frac{1}{2}} \quad (3)$$

The matching impedance ratio Z need to be the following the equation:

$$Z = \left|\frac{Z_{in}}{Z_0}\right| = \left|\sqrt{\frac{\mu_r}{\varepsilon_r}}tanh[j\frac{2\pi fd}{c}\sqrt{\mu_r\varepsilon_r}]\right| \quad (4)$$

The $|\Delta|$ value can be calculated by the following equation:

$$|\Delta| = |sinh^2(Kfd) - M| \quad (5)$$

$$K = \frac{4\pi\sqrt{\mu'\varepsilon'} \cdot sin(\frac{\delta_\varepsilon + \delta_\mu}{2})}{c \cdot cos\delta_\varepsilon \cdot cos\delta_\mu} \quad (6)$$

$$M = \frac{4\mu' \cdot cos\delta_\varepsilon \cdot \varepsilon' \cdot cos\delta_\mu}{(\mu' \cdot cos\delta_\varepsilon - \varepsilon' \cdot cos\delta_\mu)^2 + \left[tan(\frac{\delta_\mu - \delta_\varepsilon}{2})\right]^2 \cdot (\mu' \cdot cos\delta_\varepsilon + \varepsilon' \cdot cos\delta_\mu)^2}$$

(7)

where δ_ε and δ_μ are dielectric loss angle and magnetic loss angle, respectively.

CST simulation:

CST Studio Suite 2020 was employed to simulate the radar cross section (RCS). A double-layer metal back model (the upper layer is a 4.20 mm absorbent layer, and the bottom layer is a perfect conductive layer (PEC) of 2.00 mm was designed for RCS simulation analysis. The simulation frequency in all simulation conditions was set as 9.30 GHz. The frame of the model is set to a square of 180 × 180 mm.

Figures

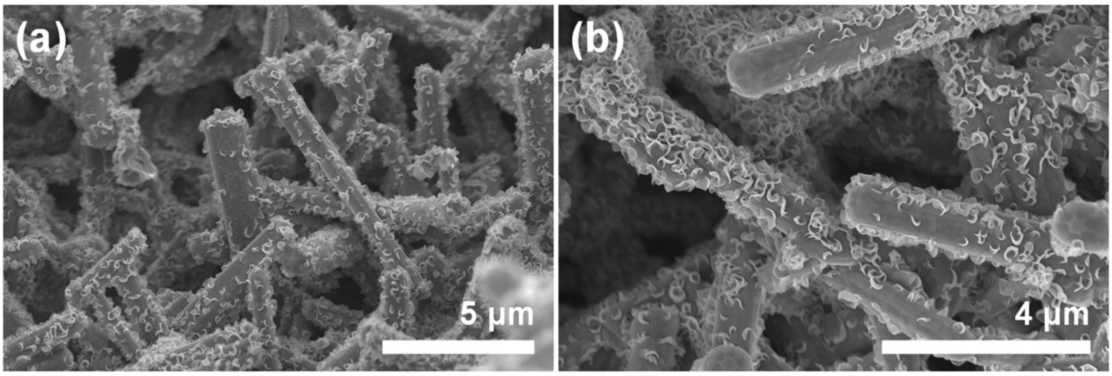

Fig. S1. SEM images of Si_3N_4@WS_2-1.

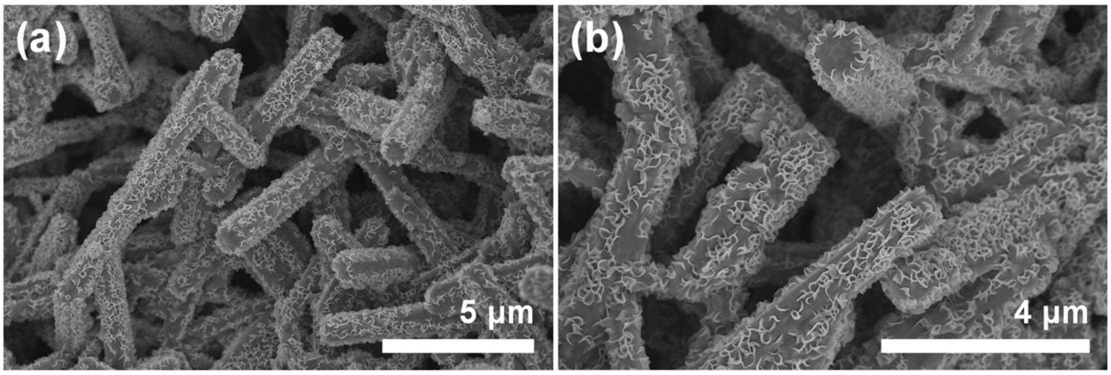

Fig. S2. SEM images of Si_3N_4@WS_2-2.

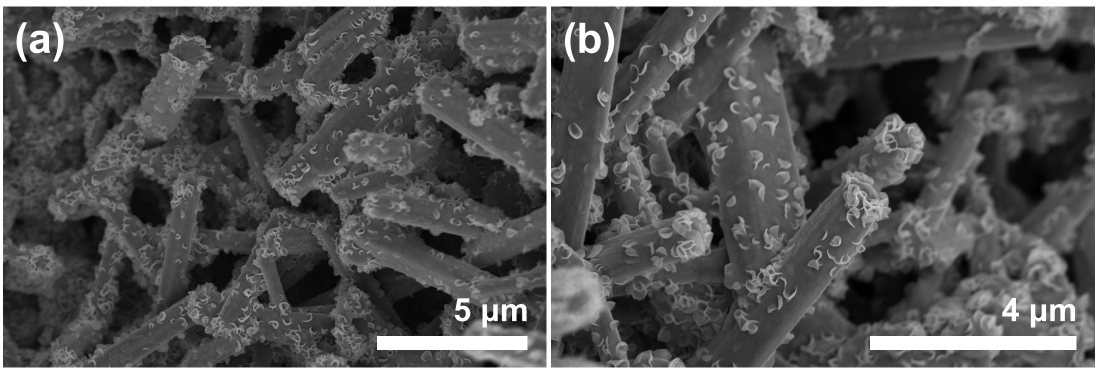

Fig. S3. SEM images of Si_3N_4@WS_2-4.

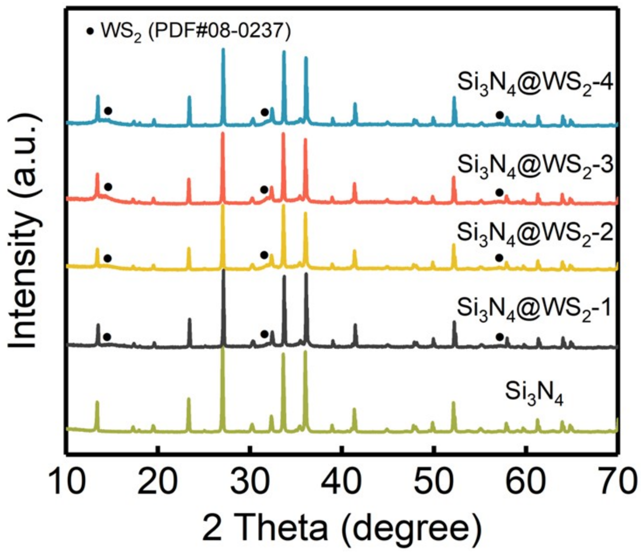

Fig. S4. XRD patterns of Si_3N_4, $Si_3N_4@WS_2$-1, $Si_3N_4@WS_2$-2, $Si_3N_4@WS_2$-3, and $Si_3N_4@WS_2$-4.

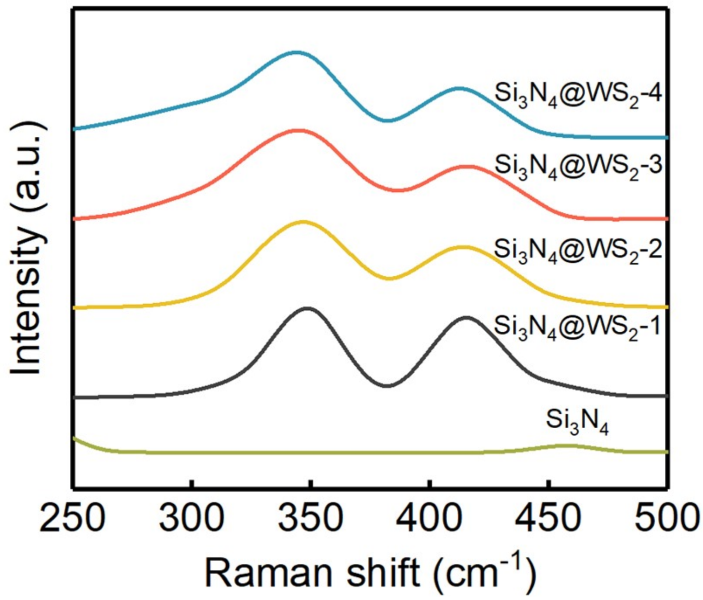

Fig. S5. Raman spectra of Si_3N_4, $Si_3N_4@WS_2$-1, $Si_3N_4@WS_2$-2, $Si_3N_4@WS_2$-3, and $Si_3N_4@WS_2$-4.

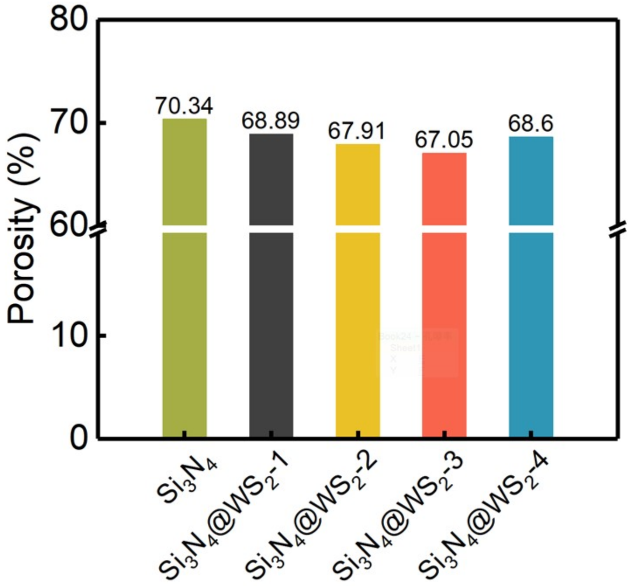

Fig. S6. Porosity of Si_3N_4, Si_3N_4@WS_2-1, Si_3N_4@WS_2-2, Si_3N_4@WS_2-3, and Si_3N_4@WS_2-4.

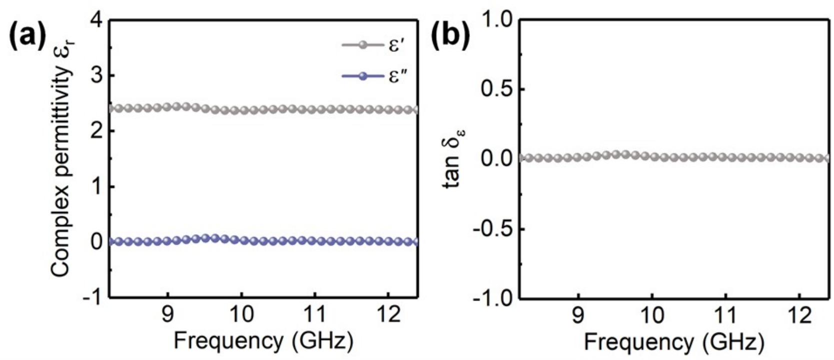

Fig. S7. Frequency-dependent (a) $\varepsilon^{'}$, $\varepsilon^{''}$, and (b) $\tan\delta_{\varepsilon}$ of Si_3N_4 porous ceramics.