High-permittivity Sb_2S_3 single-crystal nanorods as a brand-new choice for electromagnetic wave absorption

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ABSTRACT The application of antimony sulfide (Sb_2S_3) has been limited mainly to the energy storage and photoelectric conversion fields. However, in this work, the application of Sb_2S_3 is extended to the field of electromagnetic (EM) wave absorption for the first time. High-permittivity Sb_2S_3 single-crystal nanorods were prepared successfully and exhibited excellent performance, with a low reflection loss of -65.9 dB (13.0 GHz, 3.8 mm) and an ultra-wide effective absorption bandwidth of 9.5 GHz (8.5–18.0 GHz, 4.1 mm). After excluding the general absorption mechanisms, including conductive losses, interfacial polarization, and dipole polarization, the distinctive single-crystal volume polarization affected by shape anisotropy was proposed. This work not only meets the challenge of a single-component dielectric material design but also introduces a new concept for construction of efficient dielectric EM wave absorption material.

Keywords: antimony sulfide, single-crystal nanorods, high permittivity, volume polarization, electromagnetic wave absorption

INTRODUCTION

The deterioration of the electromagnetic (EM) environment has resulted in EM wave absorption materials in the gigahertz (GHz) range, which has been receiving more attention in the area of electronic interference rejection and civil physical protection [1–4]. The traditional candidates include carbon [5–7], dielectric ceramic [8–10], and ferromagnetic materials [11–13]. However, in view of the functional limitations, the single-component design strategy has been seriously challenged. Thus, most researchers have focused on multicomponent construction [1,14–16], which results in a selectable component region that lacks effective extension for long periods of time.

The antimony sulfide (Sb_2S_3) semiconductor has long

been highly desirable in the areas of energy storage and photoelectric conversion because of its single stable phase and narrow bandgap (1.5–2.2 eV) [17–20]. However, as a dielectric material, it has never been regarded as a potential candidate for EM absorption owing to its non-magnetic and low-conductivity nature, which results in scarce attenuation capacity and weak response in the EM region [21–23], until a related report opened up new possibilities. Xia *et al.* [8] studied hydrogenated multiphase TiO_2 comprehensively and noted that the polarization effect enlargement was the vital factor in enhancing the EM absorption performance of single-component dielectric materials.

However, trapped by the high-phase stability of Sb_2S_3 [17], the multiphase design is clearly irrational. Thus, enhancing polarization by shape anisotropy offers an attractive option. In a solvent–thermal reaction, taking advantage of the absorption effects of specific crystal faces for surfactants, as well as the varying solvent affinities of different orientations, the growth habit of crystals in the liquid environment can be affected significantly, leading to shape transformations in single-crystal nanoparticles [24–26].

In this paper, Sb_2S_3 is applied to the EM wave absorption field for the first time. As such, the aforementioned challenges have been addressed through the synthesis of highly dielectric Sb_2S_3 single-crystal nanorods. A significantly enhanced permittivity was achieved, leading to a minimum reflection loss (RL) value of -65.9 dB with a 3.8-mm thickness and a maximum effective absorption bandwidth (EAB; $\text{RL} \leq -10$ dB) with a 4.1-mm thickness. To clarify the intrinsic mechanisms, the phase compositions, crystal preferential orientation, microtopography, surface chemical properties, and com-

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plex permittivity were investigated comprehensively. After eliminating the general absorption mechanisms, we proposed the distinctive mechanism of single-crystal volume polarization (SCVP) as affected by shape anisotropy, which facilitated the promotion of permittivity and attenuation capacity. This work not only expands the applications of Sb_2S_3 but also introduces a new concept for construction of efficient dielectric EM wave absorption material.

EXPERIMENTAL SECTION

Chemicals

Antimony chloride (SbCl_3), *L*-cysteine ($\text{C}_3\text{H}_7\text{NO}_2\text{S}$), sodium sulfide (Na_2S), thioacetamide ($\text{C}_2\text{H}_5\text{NS}$), ethyl alcohol ($\text{C}_2\text{H}_6\text{O}$), and ethylene glycol ($\text{C}_2\text{H}_6\text{O}_2$) were purchased from Sinopharm Chemical Reagent Co., Ltd. and used without further purification. Commercial antimony sulfide ($\text{C-Sb}_2\text{S}_3$) purchased from Aladdin Chemical Reagent Co., Ltd. was selected for the comparison test.

Synthesis of irregular Sb_2S_3 nanospheres (S- Sb_2S_3)

First, 2.0 mmol of SbCl_3 was dissolved in 100 mL of ethylene glycol with stirring to form homogeneous solution A. Then, 10.0 mmol of $\text{C}_2\text{H}_5\text{NS}$ was dissolved in 100 mL of ethylene glycol with stirring to form homogeneous solution B. Subsequently, solution B was slowly poured into solution A, with subsequent vigorous stirring for 12 h. Following this, the sediment obtained was isolated by centrifugation, washed repeatedly using deionized water and alcohol, dried at 60°C for 12 h, and finally treated at 250°C under a nitrogen atmosphere for 1 h.

Synthesis of Sb_2S_3 nanorods (R- Sb_2S_3)

First, 2.5 mmol of SbCl_3 , 5.0 mmol of $\text{C}_3\text{H}_7\text{NO}_2\text{S}$, and 5.0 mmol of Na_2S were dissolved in 50.0 mL of deionized water, and the mixture was stirred for 3 h to form a suspension. Then, the solution was transferred into a Teflon-lined stainless-steel autoclave for heating at 180°C for 12 h. Finally, the sediment obtained was isolated by centrifugation, washed repeatedly using alcohol, and dried at 60°C for 12 h.

Characterization

The phase structures of different Sb_2S_3 samples were determined using powder X-ray diffraction (XRD; DMAX-2500PC), while the microstructure was characterized using field-emission scanning electron microscopy (FESEM; JSM-7610F) and high-resolution transmission electron microscopy (HR-TEM; JEOL-2100F). The sur-

face electronic properties were investigated using X-ray photoelectron spectroscopy (XPS; Thermo ESCALAB 250XI). The EM parameters in the 2.0–18.0 GHz range were measured using a vector network analyzer (VNA; Agilent PNA N5244A). In the VNA measurements, the different Sb_2S_3 powders (75 wt%) were mixed evenly with paraffin wax (25 wt%) to form a toroidal sample ($\Phi_{\text{in}} = 3.04$ mm; $\Phi_{\text{out}} = 7.00$ mm; thickness = 2.0 mm).

RESULTS AND DISCUSSION

The phase components of the different Sb_2S_3 samples were characterized using XRD. As Fig. 1 shows, all the three samples exhibited XRD patterns similar to those of stibnite antimony(III) sulfide (JCPDS No. 42-1393). No redundant peaks were observed, indicating a pure Sb_2S_3 phase. The strong peaks at 24.9°, 29.2°, and 32.4° could be identified as the (130), (211), and (221) crystal planes. However, the peak intensity of C- Sb_2S_3 was much weaker than that of the other two samples because of its polycrystalline nature. Compared with S- Sb_2S_3 , R- Sb_2S_3 exhibited a much stronger peak intensity at 24.9°, illustrating a more favorable crystal orientation of (130) crystal planes. This was because the differences in the solvent and surfactant during the crystal growth process caused the surface energy of the (130) crystal planes in R- Sb_2S_3 to be much lower, further leading to the growth along the <130> direction being suppressed. Generally, the difference in crystal preferential orientation is regarded as the key factor behind single-crystal particle shapes [24]. For this reason, R- Sb_2S_3 and S- Sb_2S_3 exhibited different microstructures.

Figure 1 XRD patterns of R- Sb_2S_3 , S- Sb_2S_3 , and C- Sb_2S_3 and the standard pattern and major indexes of Sb_2S_3 .

The nanostructure and micromorphology of R-Sb₂S₃ and S-Sb₂S₃ were characterized using FE-SEM and HR-TEM. R-Sb₂S₃ exhibited a rod-like shape, with a diameter of ~70 nm. The average length of the rods was 1.2 μ m, with the maximum extending to 3 μ m (Fig. 2a, b). S-Sb₂S₃ exhibited irregular spherical nanoparticles, with an average diameter of ~400 nm, which were aggregated together in a disordered fashion (Fig. 2c, d). The differences in particle shape supported the analysis related to the crystal preferential orientation observed in the XRD patterns. The lower magnification TEM of both R-Sb₂S₃ and S-Sb₂S₃ confirmed the solid construction. Furthermore, both the corresponding selected-area electron diffraction (SAED) patterns exhibited clear diffraction spots, thereby confirming the single-crystal nature. In addition, in the HR-TEM image of R-Sb₂S₃ (Fig. 2f), the lattice fringe distance of 0.36 nm corresponded to the (130) crystal plane. Meanwhile, in the HR-TEM image of S-Sb₂S₃ (Fig. 2h), the lattice fringe distances of 0.31 and 0.51 nm corresponded to the (211) and (120) crystal planes, respectively. This suggests that the (130) crystal plane tended to be exposed in R-Sb₂S₃. The micromorphology images of C-Sb₂S₃ (Fig. S1) revealed extremely irregular and large bulks.

The EM wave absorption performances were calculated according to the metallic back plate model and the theory of transmission line, and were evaluated according to the RL values [1,27–30]:

$$Z_{\text{in}} = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left(\frac{2\pi j f d}{c} \sqrt{\mu_r \varepsilon_r}\right), \quad (1)$$

$$RL = 20 \log \left| \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} \right|, \quad (2)$$

where Z_{in} and Z_0 are the input impedance of the absorbers and the characteristic impedance of air, respectively; j is the imaginary unit; ε_r and μ_r are the relative permittivity and permeability, respectively; f is the frequency; c is the speed of light in vacuum, and d is the matching thickness of the absorber. The real and imaginary parts of the permeability were considered to be 1.0 and 0.0, respectively, because of the nonmagnetic nature of Sb₂S₃ (Fig. S2).

We could ascertain visually that R-Sb₂S₃ possessed a stronger EM wave absorption intensity than S-Sb₂S₃ (Fig. 3a, b). The minimum RL value of R-Sb₂S₃ was up to –65.9 dB at 13.0 GHz, corresponding to the matching thickness of 3.8 mm. However, the minimum RL value of S-Sb₂S₃ reached only –23.3 dB at 11.5 GHz, corresponding to the matching thickness of 4.4 mm. In addition to the absorption intensity, R-Sb₂S₃ outperformed S-Sb₂S₃ in terms of absorption bandwidth performance. R-Sb₂S₃ also reached an ultra-wide maximum EAB (RL < –10 dB) of 9.5 GHz at the measured frequency (8.5–18.0 GHz), with a matching thickness of 4.1 mm, which surpasses that of a large number of reported EM wave absorption materials. Furthermore, the EAB of R-Sb₂S₃ covered 72.5% of the measured frequency (6.5–18.0 GHz) within the matching thickness of 1.0–5.0 mm. S-Sb₂S₃ still reached a reasonable maximum EAB of 7.3 GHz (10.0–17.3 GHz) at the same matching thickness, while the EAB of S-Sb₂S₃ covered 62.5% of the measured frequency (8.0–18.0 GHz) within the matching thickness of 1.0–5.0 mm. As shown

Figure 2 FE-SEM images and particle size distributions of (a, b) R-Sb₂S₃, and (c, d) S-Sb₂S₃; HR-TEM images and selected area electron diffraction patterns of (e, f) R-Sb₂S₃, and (g, h) S-Sb₂S₃.

Figure 3 Three-dimensional RL values of (a) R-Sb₂S₃ and (b) S-Sb₂S₃; RL value projection maps of (c) R-Sb₂S₃ and (d) S-Sb₂S₃; (e) the permittivities of R-Sb₂S₃ and S-Sb₂S₃; (f) the dielectric tangent losses of R-Sb₂S₃ and S-Sb₂S₃.

in Fig. S3, the RL values of C-Sb₂S₃ indicated an extremely unsatisfactory EM absorption performance ($RL_{\min} = -1.9$ dB).

Meanwhile, the comparison of the matching thickness should be performed at the same frequency because of the negative correlation between frequency and matching thickness. Taking the frequency of 10.0 GHz as an example, the minimum thickness to ensure that the RL value could reach -10 dB for S-Sb₂S₃ was 4.1 mm. However, for R-Sb₂S₃, the same absorption condition could be achieved at 3.7 mm. Similar conclusions could be obtained at other frequencies. Therefore, R-Sb₂S₃ was also far superior to S-Sb₂S₃ in terms of matching thickness.

To determine why R-Sb₂S₃ exhibited better EM wave absorbing performances, its permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) was investigated, with the results shown in Fig. 3e. The real part of the permittivity reflected the electrical storage capacity [2,31]. Both R-Sb₂S₃ and S-Sb₂S₃ exhibited a downtrend of ϵ' values over the whole measured frequency range. The ϵ' values declined from 6.2 to 2.3 and from 4.2 to 2.3 for R-Sb₂S₃ and S-Sb₂S₃, respectively. At a lower frequency range ($f < 10$ GHz), the ϵ' values of R-Sb₂S₃ were clearly larger than those of S-Sb₂S₃; however, at a higher frequency range, both curves were almost the

same. This indicated that R-Sb₂S₃ possessed an enhanced electrical storage capacity in comparison with S-Sb₂S₃ only at the low-frequency range.

Meanwhile, the imaginary part of permittivity is related to the electrical dissipation ability [2,32]. Each of the samples exhibited a broad resonance peak over the whole frequency range measured. The ϵ'' value of S-Sb₂S₃ increased from 0.4 to 1.6 within the frequency range of 2.0–11.4 GHz, before decreasing to 1.0 within the frequency range of 11.4–18.0 GHz. The ϵ'' value of R-Sb₂S₃ rose from 1.2 to 2.7 within the frequency range of 2.0–7.2 GHz, before decreasing to 1.2 at 18.0 GHz. The average ϵ'' value for R-Sb₂S₃ (2.205) was 1.84 times that of S-Sb₂S₃ (1.197), which indicated that the electrical dissipation ability of R-Sb₂S₃ achieved a significant enhancement. Moreover, the frequency of the maximum ϵ'' value for R-Sb₂S₃ (2.7 at 7.2 GHz) was much lower than that of S-Sb₂S₃ (1.6 at 11.4 GHz), which resulted in more effective absorption at a lower frequency and further widening of the EBA for R-Sb₂S₃.

The dielectric loss tangent ($\tan\delta_E = \epsilon''/\epsilon'$) was used to evaluate the amount of wave energy stored in relation to the amount of wave energy consumed (Fig. 3f), which reflects the intrinsic attenuation capacity [2]. Both S-Sb₂S₃

and R-Sb₂S₃ exhibited overall trends of falling after rising. Specifically, the $\tan\delta_E$ value of S-Sb₂S₃ increased from 0.11 to 0.59, before decreasing to 0.53 at 18.0 GHz, whereas the $\tan\delta_E$ value of R-Sb₂S₃ shifted from 0.21 to 0.89, decreasing subsequently to 0.42 at 18.0 GHz. Both samples reached the maximum at 11.6 GHz. Clearly, R-Sb₂S₃ possessed higher $\tan\delta_E$ values than S-Sb₂S₃, indicating that more of the EM energy that entered the materials could be dissipated into heat with R-Sb₂S₃. Both the complex permittivity and the dielectric tangent loss of C-Sb₂S₃ were used to determine the lossless characteristic of the EM waves, with the results shown in Fig. S4. In addition to the loss tangent, the attenuation coefficient (α) confirmed the attenuation capacity differences (Fig. S5).

For single-component materials, interfacial polarization should not be considered. This was the case here, because the charge accumulation on the Sb₂S₃/paraffin interfaces had to be excluded owing to the insulating nature of paraffin wax ($\sigma < 10^{-11} \text{ S m}^{-1}$). However, the dipole rotation/polarization or defects/vacancies are potentially responsible for the enhancement of the attenuation capacity because of the excitation of the alternating electric field. Thus, XPS was used to determine whether functional groups or vacancies were produced in the Sb₂S₃ crystals during different synthetic processes. The S 2p, S 2s, Sb 3d, and Sb 3p electronic orbits could be observed clearly in the survey scan spectrum (Fig. 4a). In the high-resolution Sb 3d spectrum (Fig. 4b), the two signals observed at 529.5 and 538.8 eV with an energy gap of 9.3 eV could be regarded as the Sb 3d_{5/2} and Sb 3d_{3/2} orbitals of Sb³⁺ in Sb₂S₃ [33,34], whereas the low and inconspicuous peak at 530.1 eV was related to the Sb 3d_{5/2} orbitals of Sb³⁺ in Sb₂O₃ [33,35]. Although this indicated that few sulfur atoms were replaced by oxygen atoms on the surface during storage, this fact could be ignored. Meanwhile, the oxygenic signal was more notable in C-Sb₂S₃ (Fig. S6). The high-resolution S 2p orbital (Fig. 4c) was

divided into the S 2p_{3/2} and S 2p_{1/2} orbitals located at 161.6 and 162.8 eV, respectively, which implied the existence of S-Sb bonds in Sb₂S₃ [33,36]. We ascertained that there was almost no difference between R-Sb₂S₃ and S-Sb₂S₃ from the XPS spectra. Therefore, both the functional groups and the defects/vacancies were unlikely to result in the significant enhancement of EM absorption performances.

Neither ionic polarization nor electron polarization (10^3 – 10^6 GHz) apply to the frequency range discussed in this work [37,38]. General interfacial polarization and dipole polarization were also excluded in the above analysis. However, using the Debye theory, we ascertained that the polarization-relaxation mechanism undoubtedly contributed to the improvement of the dielectric dissipation capacity. According to the Debye theoretical models, for low-conductivity materials, the complex permittivity can be described by the following equations [15,38–41]:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2 \tau^2}, \quad (3)$$

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

where ε_s and ε_∞ are the static permittivity and the permittivity at the high frequency limit, respectively, and ω and τ represent the angular frequency and polarization-relaxation time, respectively. On combining the two equations to remove the influence of frequency and relaxation time, the following equation could be obtained [42]:

$$\left(\varepsilon' - \frac{\varepsilon_s + \varepsilon_\infty}{2} \right)^2 + (\varepsilon'')^2 = \left(\frac{\varepsilon_s - \varepsilon_\infty}{2} \right)^2. \quad (5)$$

Thus, the polarization-relaxation processes can be described as one semicircle in the plot of the ε' vs. ε'' curve, which is generally known as a Cole-Cole plot. As Fig. 5a shows, both R-Sb₂S₃ and S-Sb₂S₃ exhibited one single

Figure 4 XPS spectra of R-Sb₂S₃ and S-Sb₂S₃: (a) survey scan spectra; (b) Sb 3d spectra; and (c) S 2p spectra.

Figure 5 (a) The Cole–Cole plots of R-Sb₂S₃ and S-Sb₂S₃; schematic diagram of charge density distribution in the single-crystal particles before/after the electric field excitation for (b) R-Sb₂S₃ and (c) S-Sb₂S₃.

semicircle, demonstrating that there was a single polarization–relaxation process in the measured frequency range. Furthermore, R-Sb₂S₃ exhibited a larger semicircle than S-Sb₂S₃, implying a stronger polarization–relaxation process and enhanced polarization–relaxation losses. Generally, besides the polarization loss, the dielectric loss consists of conductive loss [43,44]. However, no upward tails at the end of the curves were observed, indicating that the conductive loss did not contribute to EM wave dissipation [45,46].

Therefore, we proposed that the mechanism of enhanced EM wave absorption for Sb₂S₃ single-crystal nanorods is the SCVP affected by shape anisotropy. The homogeneous nature of single crystals resulted in the charges being distributed evenly in the crystal. When stimulated by an alternating electric field, the charges moved alternately toward the crystal edges to form the volume polarization, which resembled a micro-capacitor with continuous charge–discharge. Benefiting from the high shape anisotropy of R-Sb₂S₃, a more prominent charge-accumulative effect could be achieved to enlarge the dissipation of the electric field energy. A schematic diagram of the charge density distribution before/after the electric field excitation for the single-crystal Sb₂S₃ particles is presented in Fig. 5b, c. Here, R-Sb₂S₃ exhibited a stronger EM absorption capacity than S-Sb₂S₃. For C-Sb₂S₃, the abovementioned SCVP mechanism could not be identified (Fig. S7), because of its bulk and polycrystalline nature. In addition, the non-semicircle curve for C-Sb₂S₃ demonstrated the nonexistence of interfacial polarization on the Sb₂S₃/paraffin interfaces.

Besides the enhanced dissipation ability, we noted that the improved permittivity in R-Sb₂S₃ could also optimize the impedance matching characteristic. An excellent impedance matching characteristic requires that the $|Z_{\text{in}}/Z_0|$ value is equal to 1, meaning that the incident EM waves

could easily enter the material rather than be reflected on the surface [12,45]. Here, the Z curve (where $|Z_{\text{in}}/Z_0| = 1$; details in Fig. S8) of R-Sb₂S₃ was located at a lower thickness region than that of S-Sb₂S₃ at the same frequency (Fig. 6a), which resulted in a thinner matching thickness in terms of EM absorption performances. Meanwhile, the slope of R-Sb₂S₃ was gentler than that of S-Sb₂S₃ when the $|Z_{\text{in}}/Z_0|$ values were close to 1 (yellow region, Fig. 6b). This implied that R-Sb₂S₃ possessed the optimized impedance matching characteristic over a larger frequency range to broaden the EAB.

The EM wave absorption performances of many absorbers obey the quarter-wavelength cancelation law because of the primary function of destructive interference. If the EM waves incident on the air–absorber interface are out of phase by 180° in relation to those reflected on the absorber–backboard interface, the destructive interference leads to the disappearance of any reflected waves, which implies that all EM waves are trapped inside the absorber to form standing waves [10,27]. As such, the minimum RL value can be achieved. The experimental matching thickness (t_{EM}) could be obtained from the EM wave absorption performances, while the theoretical matching thickness (t_{TM}) to satisfy the quarter-wavelength cancelation law could be calculated as follows [6,10,27]:

$$t_{\text{TM}} = \frac{nc}{4f\sqrt{|\mu_r||\epsilon_r|}} \quad n = 1, 3, 5 \dots \quad (6)$$

The t_{TM} curves of R-Sb₂S₃ and S-Sb₂S₃ were drawn on the corresponding RL value projection maps. However, there was clearly a deviation between the t_{EM} and t_{TM} curves for both R-Sb₂S₃ (Fig. 6c) and S-Sb₂S₃ (Fig. 6d) and the t_{EM} curves were located on a thicker region than the t_{TM} curves. This indicated that the dependence of the absorption performance on the quarter-wavelength can-

Figure 6 (a) The Z curves and (b) the $|Z_{in}/Z_0|$ values at 3.8 mm of R-Sb₂S₃ and S-Sb₂S₃; the t_{EM} and t_{TM} curves of (c) R-Sb₂S₃ and (d) S-Sb₂S₃ on the RL value projection map.

celation law was reduced significantly. Thus, we speculated that this characteristic would be favorable for Sb₂S₃ absorbers applied in the case of different incident angles.

CONCLUSIONS

In this work, Sb₂S₃ single-crystal nanorods and nanospheres were prepared successfully using different solvent-thermal methods. The preferential crystal orientation, phase structures, microtopography, chemical states, complex permittivity, and EM wave absorption mechanisms were studied comprehensively. The Sb₂S₃ nanorods possessed a diameter of ~70 nm and a maximum length of ~3 μ m and exhibited a superior EM wave absorption performance. The minimum RL value reached up to -65.9 dB at 13.0 GHz with the matching thickness of 3.8 mm, while the maximum EAB was 9.5 GHz (8.5–18.0 GHz), which surpasses the performances reported in several studies. The excellent absorption performances were because of both the enhanced attenuation capacity and the optimized impedance matching characteristic. After excluding the general absorption mechanisms, such as conductive losses, interfacial polarization, and dipole polarization, the distinctive SCVP affected by shape anisotropy was proposed. This study presented for the first time that Sb₂S₃ has been

applied in the EM wave absorption field. As such, the study not only expands the applications of Sb₂S₃ but also introduces a new concept for construction of efficient dielectric EM absorption material.

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Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Supporting data are available in the online version of the paper.

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电磁波吸收材料的新选择: 高介电常数的Sb₂S₃单晶纳米棒

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摘要 硫化锑(Sb₂S₃)的用途主要局限在储能和光电转换领域,而在本工作中, Sb₂S₃被首次拓展到电磁波吸收领域. 高介电常数的Sb₂S₃单晶纳米棒表现出了−65.9 dB的反射损耗(13.0 GHz, 3.8 mm),以及可达9.5 GHz (8.5–18.0 GHz, 4.1 mm)的超宽有效吸收带宽. 在排除了常见的吸收机制,例如导电损耗、界面损耗和偶极子损耗之后,我们提出了一种独特的形状各向异性影响下的单晶体极化机制(SCVP). 该工作不仅突破了单组份介电吸波材料设计这一挑战,也为构建高效介电吸波材料提供了新的方法和思路.