RSC Advances



Cite this: RSC Adv., 2014, 4, 40456

Synthesis of hierarchical sword-like cobalt particles and their microwave absorption properties

Shulai Wen, Xiuchen Zhao,* Ying Liu, Jingwei Cheng and Hong Li

In this paper, we reported synthesis of the cobalt particles with a hierarchical sword-like structure through a liquid reduction method. We have investigated the electromagnetic properties of the cobalt particles in the microwave frequency range of 2–18 GHz. The cobalt particles presented multiple dielectric and magnetic resonance peaks, which are related to their unique structure. We have predicted the microwave absorption properties of the cobalt particles according to the transmit line theory. The maximum reflection loss (RL) of the cobalt particles reaches -60.13 dB, and the effective absorption bandwidth (RL ≤ -10 dB) is 5.42 GHz corresponding to a thickness of 1.4 mm, revealing better microwave absorption than previously reported materials. The superior microwave absorption properties indicate that the as-prepared cobalt particles have potential application as candidates for microwave absorption.

Received 13th June 2014 Accepted 22nd August 2014

DOI: 10.1039/c4ra05716c

www.rsc.org/advances

1 Introduction

Due to intense demands for reduction of electromagnetic pollution/radiation and shielding interference in electric communication field, increasing attentions have been focused on microwave absorption materials in the GHz range.1-6 For magnetic metallic materials, the higher permeability could be obtained due to higher saturation magnetization according to Snoek's limit.7-11 Nevertheless, due to eddy current loss induced by the electromagnetic wave in GHz range, the permeability would decrease. The method to overcome eddy current loss is to make the magnetic materials be isolated in the insulator. Therefore, many nanocomposites with core@shell structure were synthesized, such as Ni@C,12 Fe@C,13 Fe@SiO2,14 Ni-Co-P@SiO₂,¹⁵ FeCoNi@C,¹⁶ and so on. It is well known that the saturation magnetization of magnetic metallic particles decrease with the size decreasing, and the nanocomposites possess lower permeability due to their size in nanoscale. Another effective way is to synthesize magnetic metallic particles with complex structure, which could avoid the eddy current loss.

As a typical magnetic metallic material, cobalt has unique physical properties for microwave absorption. Cobalt possesses high saturation magnetization, and high permeability could therefore be achieved according Snoek's limit. Moreover, cobalt has high Curie temperature, which results in cobalt used as candidate for microwave absorption in a wide temperature range. It is well known that microwave performance and absorption are related to crystal structures, and cobalt has multiple crystal structures to study microwave performance, such as hcp, fcc and bcc,¹⁷ and many interesting physical properties related to crystal structure could be exhibited. Therefore, there are wide academic and practical values to study the microwave performance and absorption for cobalt.

In this work, we synthesized cobalt particles, with plate-, sphere-chain, spherical and sword-like morphologies, through liquid phase reduction method. In this method, $CoSO_4 \cdot 7H_2O$ acted as cobalt source, $N_2H_4 \cdot H_2O$ acted as reducing agent, $C_{16}H_{33}(CH_3)_3NBr$ acted as surfactant agent, $C_4O_6H_4KNa \cdot 4H_2O$ acted as complex agent, and NaOH acted as pH adjusting agent. We systematically investigated the effects of temperature, NaOH concentration and $[C_4H_4O_6]^{2-}/Co^{2+}$ ratio on the morphologies of cobalt particles. The electromagnetic and microwave absorption properties for sword-like cobalt particles were investigated in the microwave frequency range of 1–18 GHz.

2 Experimental

2.1 Preparation of cobalt particles

All chemicals used in this work were of analytical grade and were used as received without further purification. The synthesis of cobalt particles was carried out in a 3-necked flask equipped with an ultrasound reactor. In a typical synthesis, 2.8 g $CoSO_4 \cdot 7H_2O$ and 2.8 g $C_4O_6H_4KNa$ were dissolved in 150 mL deionized water under vigorously stirring for 40 min at 40 °C, followed by 14 g NaOH. Then 10 mL $N_2H_4 \cdot H_2O$ (80 wt%) was added to the above solution. The reaction temperature was 80 °C, the power was 1400 W, and the ultrasonic frequency was 40 kHz. The dark grey precipitates were separated, washed with deionized water and absolute ethanol three times, and dried under vacuum at 40 °C for 24 h.



View Article Online

View Journal | View Issue

School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, People's Republic of China. E-mail: yingliu@bit.edu.cn; abc.1984816@163. com

2.2 Instruments and measurements

The X-Ray diffraction (XRD) patterns were recorded on a Bruker D8 Advance diffractometer in Mo K_{\alpha} radiation ($\lambda = 0.7093$ Å) operated at 50 kV and 30 mA. The scanning electron microscopy (SEM) images were obtained using a QUANTA600 scanning electron microscope operated at 25 kV. Transmission electron microscopy (TEM) images and the corresponding selected-area electron diffraction (SAED) pattern were obtained with a JEOL JEM-2010 microscope at 200 kV. The magnetization measurement was performed by vibrating sample magnetometer (VSM). The complex permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$) and relative complex permeability ($\mu_r = \mu' - j\mu''$) were determined using the *T/R* coaxial line method in the range of 1–18 GHz with an O-ring shaped sample (i.d. = 3 mm, o.d. = 7 mm and thickness d = 2 mm) using an HP8722ESS vector network analyzer.

3 Results and discussion

Fig. 1 shows the XRD pattern of as-prepared samples. The peaks at $2\theta = 18.86^{\circ}$, 21.40° and 35.96° match very well with the (100), (101) and (103) planes of hcp-cobalt. The peaks at $2\theta = 23.09^{\circ}$ and 40.56° can be well indexed to the (200) and (222) planes of fcc-cobalt. The remaining are overlap peaks of hcp and fcc-cobalt. The result demonstrates that the as-synthesized samples are a mixture of hcp and fcc-cobalt. No impurity peaks were detected in the XRD pattern, such as Co(OH)₂, CoO and so on, which indicated the as-prepared samples were pure.

Fig. 2 shows the morphology of cobalt particles. Hierarchic sword-like cobalt particles, assembled by sword-like flakes, were observed. The size of cobalt particles is ~8 µm, and the thickness of sword-like flakes is ~1 µm. Further observation that each leaf seems to grow from the same center, and each sword-like flake consists of a long central main branch and very blunt secondary branches. The secondary branches preferentially grow along two definite directions rather than exhibit randomly ramified grown, as shown in Fig. 2(a and b). The SAED pattern (Fig. 2(d)), corresponding to the circles area in Fig. 2(c), illustrates a perfect single crystal nature for sword-like flakes. As shown in Fig. 2(d), the [001] direction corresponding to the (002) plane of hcp-cobalt is parallel to the grown direction of the main branch, as displayed by the arrow in Fig. 2(c). However,



Fig. 1 The XRD pattern of the as-synthesized samples.



Fig. 2 The SEM and TEM images of the cobalt particles. (a) SEM image of the cobalt particles (2.5k); (b) SEM image of the cobalt particles (5k); (c) TEM image of the cobalt particles; (d) the selected-area diffraction (SAED) pattern of the circles area in (c).

the [101] direction is parallel to the grown direction of secondary branches. These indicate that the growths of the main branch and secondary branches are along [001] and [101] directions, respectively. The XRD pattern shows that main phase for as-synthesized sample is fcc-cobalt, not agreeing with the SAED pattern. The reason may be that at the early stage, the formation of fcc-cobalt occurs due to high deposition rate of cobalt atoms, and then the deposition rate of cobalt atoms become slower at the later stage, causing hcp-cobalt formed. So the SAED pattern on the edge of leaf-like flake illustrates hcpcobalt structure.

Fig. 3 shows effect of temperature and concentration of NaOH on the morphology of cobalt particles. From left to right, when the concentration of NaOH remains the same, with the reaction temperature increasing, the cobalt particles tend to fractal grown. From bottom to top, improving the concentration of NaOH is beneficial to fractal grown in the cobalt particles when the temperature is equal. Cobalt particles with different morphologies are obtained by adjusting the reaction temperature and concentration of NaOH, respectively. In particular, it is interesting that cobalt particles with ball-chain structure were achieved when the reaction temperature is 40 °C, and the concentration is 0.5 mol L^{-1} and 1 mol L^{-1} , respectively, as shown in Fig. 3(g and j), which is related to magnetic interaction between cobalt particles.

Fig. 4 shows effect of temperature and $[C_4H_4O_6]^{2-}/Co^{2+}$ ratio on the morphology of cobalt particles. From left to right, it is beneficial to fractal grown by improving the temperature when $[C_4H_4O_6]^{2-}/Co^{2+}$ ratio is equal. From bottom to top, the morphology of cobalt particles tends to fractal grown by decreasing the $[C_4H_4O_6]^{2-}/Co^{2+}$ ratio when the reaction temperature remains the same. Further observed that cobalt particles with ball-chain structure were also obtained when



Fig. 3 Effect of temperature and concentration of NaOH on the morphology of cobalt particles (a) 40 °C, 7 mol L⁻¹; (b) 65 °C, 7 mol L⁻¹; (c) 80 °C, 7 mol L⁻¹; (d) 40 °C, 4 mol L⁻¹; (e) 65 °C, 4 mol L⁻¹; (f) 80 °C, 4 mol L⁻¹; (g) 40 °C, 1 mol L⁻¹; (h) 65 °C, 1 mol L⁻¹; (i) 80 °C, 1 mol L⁻¹; (j) 40 °C, 0.5 mol L⁻¹; (k) 65 °C, 0.5 mol L⁻¹; (m) 80 °C, 0.5 mol L⁻¹.

temperature was 40 $^\circ C$ and the $[C_4 H_4 O_6]^{2-}/Co^{2+}$ ratio was 3, as shown in Fig. 4(d).

In general, the morphology of cobalt particles is ascribed to the formation rate of cobalt atoms. A fast reduction rate of Co^{2+} results in a high cobalt atom concentration, which is beneficial to promote one-dimensional grown of cobalt. The faster the reduction rate of Co^{2+} is, the more obvious the branching ratio in the cobalt particles. Conversely, a slower reduction rate promotes the formation of ball structure of cobalt particles. According to the following chemical reactions:¹⁸⁻²⁰

$$\operatorname{Co}^{2^+} + n(\operatorname{C}_4\operatorname{O}_6\operatorname{H}_4)^{2^-} \leftrightarrow [\operatorname{Co}(\operatorname{C}_4\operatorname{H}_6\operatorname{O}_4)]_n^{2-2n}$$
 (1)

$$\begin{aligned} [\text{Co}(\text{C}_{4}\text{O}_{6}\text{H}_{4})]n^{2-2n} + 3\text{N}_{2}\text{H}_{4} \rightarrow \\ [\text{Co}(\text{N}_{2}\text{H}_{4})_{3}]^{2+} + n(\text{C}_{4}\text{O}_{6}\text{H}_{4})^{2+} \end{aligned} \tag{2}$$

$$\begin{bmatrix} \text{Co}(\text{N}_2\text{H}_4)_3 \end{bmatrix}^{2^+} + \text{N}_2\text{H}_4 + \text{OH}^- \rightarrow \\ \text{Co}\downarrow + \text{N}_2\uparrow + \text{H}_2\uparrow + \text{NH}_3\uparrow + \text{H}_2\text{O}$$
(3)

According to the chemical reaction (3) and (4), the reduction rate of Co^{2+} could be promoted though decreasing the $[\text{C}_4\text{H}_4\text{O}_6]^{2-}/\text{Co}^{2+}$ ratio or improving the concentration of NaOH, being beneficial to the fractal grown in the cobalt particles. Meanwhile, the reduction ability of $N_2\text{H}_4\cdot\text{H}_2\text{O}$ is directly determined by the concentration of NaOH or $[\text{C}_4\text{H}_4\text{O}_6]^{2-}/\text{Co}^{2+}$ ratio, controlling formation rate of cobalt atoms. As well known, improving the reaction temperature could also promote the reduction rate of Co^{2+} , and tend to the fractal grown. Therefore, the hierarchic sword-like morphology of cobalt particles is the result of comprehensive action of the reaction factors.

Fig. 5 shows magnetic hysteresis loop for cobalt particles at room temperature. We can see that the saturation



Fig. 4 Effect of temperature and $[C_4H_4O_6]^{2-}/Co^{2+}$ ratio on the morphology of the cobalt particles (a) 40 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 6$; (b) 65 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 6$; (c) 80 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 6$; (d) 40 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 3$; (e) 65 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 3$; (f) 80 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 3$; (g) 40 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 1$; (h) 65 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 1$; (j) 40 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 0$; (k) 65 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 0$; (m) 80 °C, $[C_4H_4O_6]^{2-}/Co^{2+} = 0$.

magnetization (M_s) of cobalt particles is 150.17 emu g⁻¹, less 7% than that of bulk cobalt (162 emu g⁻¹).²¹ The reduction in M_s for the cobalt particles is ascribed to formation of oxides on the particle's surface and a decrease in crystallinity. The former introduces paramagnetism and instead the latter introduces superparamagnetism. The coercivity (H_c) for samples is 100.34 Oe, much larger than that of bulk cobalt (10 Oe).^{22,23} H_c can be expressed as:^{24,25}

$$H_{c,n} = \frac{\mu}{R^3} (6K_n - 4L_n)$$
(4)

where μ and *R* are the dipole moment and the diameter of each sphere. The expression takes into account the dipolar interaction between the magnetic spheres in the chain based on the assumption of fanning mode. In particular, *K*_n accounts for the dipolar interaction between each every pair of the magnetic

particles, and L_n , between each odd-numbered and evennumbered pairs. The number, n, is for the sphere numbering in the chain. According to the equation, H_c is inversely proportional to R^3 , so H_c of sword-like cobalt particles is larger due to cobalt particles in micron scale. Moreover, hcp-cobalt in cobalt particles could improve coercivity of cobalt particles due to larger magnetocrystalline anisotropy energy. The stacking fault could also improve the coercivity for cobalt particles.²⁶ Therefore, enhanced coercivity for sword-like cobalt particles is a comprehensive consequence of size, crystal phase and stacking fault.

The reflection loss (RL) for sword-like cobalt particles was calculated using the complex permittivity and permeability at given frequency and thickness layer according to the transmit line theory, which is summarized as the following equations:^{27,28}



Fig. 5 The hysteresis loop of the sword-like cobalt particles (at room temperature).

$$Z_{\rm in} = Z_0 \sqrt{\frac{\mu_{\rm r}}{\varepsilon_{\rm r}}} \tanh\left[j\frac{2\pi}{c}\sqrt{\mu_{\rm r}\varepsilon_{\rm r}}fd\right] \tag{5}$$

$$\mathrm{RL}(\mathrm{dB}) = Z_0 \log \left| \frac{Z_{\mathrm{in}} - Z_0}{Z_{\mathrm{in}} + Z_0} \right| \tag{6}$$

where Z_0 is the impedance of the free space, Z_{in} is the input impedance, μ_r and ε_r are the relative permeability and permittivity of the absorber, respectively, f is the frequency of the electromagnetic wave, d is the thickness of the absorber, and c is the velocity of the light in free space. The complex permeability and permittivity were tested on a network analyzer with the frequency of 1-18 GHz. The calculated reflection loss for the paraffin-based composite with 70 wt% cobalt particles is shown in Fig. 6. A maximum reflection loss of -60.13 dB at 13.72 GHz was obtained for cobalt particles corresponding to a thickness of 1.4 mm, and the absorption bandwidth ($RL \le -10 \text{ dB}$) is 5.42 GHz in Fig. 6(a). Moreover, the effect absorption bandwidth (RL ≤ -20 dB) of 1.75 GHz was achieved. Strong and high-efficiency microwave absorption property for cobalt particles has been exhibited, and it is expected to be used as absorbers for electromagnetic microwave absorption and shielding fields. Fig. 6(b) shows the dependence of reflection loss on the thickness in the range of 1-18 GHz. It can be seen that microwave absorption below -10 dB can be achieved as long as the

thickness is in the range of 1.01-4.73 mm, and an absorption exceeding -20 dB is obtained for the thickness of 1.11-1.97 mm. Table 1 shows the comparison of the cobalt particles and other representative materials in earlier literatures. We can see that the as-prepared cobalt particles have potential application as candidate for microwave absorption.

To investigate the possible microwave absorption mechanism for sword-like cobalt particle, complex permittivity and permeability behaviors have been studied as shown in Fig. 7. Three resonance peaks were achieved for real part of permittivity at 7.43, 13.27, 17.30 GHz, respectively. Lagging behind resonance peaks for real part, both imaginary part and dielectric loss exhibit four resonance peaks at 3.40, 9.08, 13.48 and 17.63 GHz. Further observed that permittivity and dielectric loss increase with frequency increasing in the range of 1-18 GHz as shown in Fig. 7(a), which may be due to the defect in the cobalt particles. In general, permittivity usually stems from orientation polarization, atomic polarization and electronic polarization.^{33,34} Normally, the resonance caused by vacancy or pores usually dominates in the low-frequency regions. Atomic and electronic polarization is contributed to high-frequency resonance. Therefore, multi-nonlinear dielectric resonance is a comprehensive result of atomic and electronic polarization.

Fig. 7(b) shows the real part of permeability (μ') deceases from 1.87 to 0.39 with frequency increasing. Multiple resonance peaks were exhibited for imaginary part (μ'') of permeability at 5.73, 11.60 and 15.26 GHz. For magnetic materials, the magnetic loss mainly stems from magnetic hysteresis, domain wall resonance, natural resonance³⁵ and exchange resonance.³⁶ Magnetic hysteresis originates from irreversible magnetization occurs in a highly applied field, while domain wall movement derived from multi-domain materials occurs in the low frequency (<2 GHz). However, resonance resulting from spin rotational component occurs at high-frequency range.³⁷ Therefore magnetic loss for sword-like cobalt particles could be ascribed to natural resonance and exchange resonance.

To investigate the magnetic loss, we introduced the equation, $\mu''(\mu')^{-2}f^{-1} = \frac{2}{3}\pi\mu_0 d^2\sigma$,^{38,39} where μ_0 is the vacuum permeability, μ' is the real part of permeability, μ'' is the imaginary part of permeability, σ is the conductivity, f is the frequency, d is the thickness of the sample. According to the



Fig. 6 Frequency dependence of reflection loss of cobalt particles in the range of 1–18 GHz.

Table 1 ⊤	he comparison of	microwave absorption	between as-prepared	cobalt particles and	other representative materials
-----------	------------------	----------------------	---------------------	----------------------	--------------------------------

Sample	$RL_{max}\left(dB ight)$	$d_{ m m} (m mm) \ (m RL \leq -20 d m B)$	Frequency (GHz) $(RL \le -20 \text{ dB})$	Percentage (wt%)	Reference
Fe/SmO	-52.00	7.9–13.1	0.73-1.3	80	29
Fe/Y ₂ O ₃	-36.00	3-5	2-3.5	80	30
Fe ₃ Al/Al ₂ O ₃	-45.00	1.5-2.5	7.2-17.4	75	31
C/Co	-40.00	5	4.2	30	32
MWCNTs/Co	-37.00	4.18-6.82	2.35-3.51	60	16
Sword-like Co	-60.13	1.1–1.92	11.87-17.85	70	This work

equation, if the values of $\mu''(\mu')^{-2}f^{-1}$ is constant with frequency changing, magnetic loss only stems from the eddy current. If not, the magnetic loss is ascribed to natural resonance and exchange resonance. Fig. 8 shows frequency dependence of $\mu''(\mu')^{-2}f^{-1}$ in the range of 1–18 GHz. We can see that the value of $\mu''(\mu')^{-2}f^{-1}$ deceases with frequency increasing, indicating that magnetic loss of sword-like cobalt particles resulted from a consequence of natural resonance and exchange resonance.

The first resonance peak at 5.73 GHz is due to natural resonance.40 When the frequency of incident microwave accords with the intrinsic frequency of the magnetization spinning oscillation along the effective anisotropic field, the natural resonance would occur in magnetic particles. The natural resonance frequency is given by $f_r = (\gamma_0/2\pi) \times H_{e_1}^{40,41}$ with γ_0 the gyromagnetic ratio, 2.6 GHz/T (ref. 42) and H_e the effective anisotropic field. The anisotropic field depends on the crystalline anisotropy, particles morphology and the magnetic interaction between particles. For bulk cobalt, the effective anisotropy field is only ascribed to its crystalline anisotropy. The magnetocrystalline anisotropy field $H_k = -\frac{4K_1}{3\mu_0 M_s}$ (fcc-Co, $K_1 =$ -6.5×10^4 J m⁻³, hcp-Co, $K_1 = 5.2 \times 10^5$ J m⁻³). However, the as-synthesized cobalt particles are sword-like structure, and so the particles morphology also influences the effective anisotropy field through its demagnetization field. Therefore, the natural resonance frequency is given by $f_{\rm r} = (\gamma_0/2\pi) \times (H_{\rm c} + H_{\rm k})$, where H_c is the shape anisotropy field. The broader resonance peak is attributed to the particles size distributions, disordered particles orientation or the larger intrinsic damping parameter of the cobalt particles.43,44

The two resonance peaks at 11.60 and 15.26 GHz is ascribed to exchange resonance. Multiple resonance problem is an interesting subject which is widely discussed in the reported literatures. And the famous and successful idea is exchange resonance mode developed by Aharoni.44 When the magnetic particles size is in nanoscale, the exchange energy among magnetic particles becomes important compared with magnetostatic energy. The exchange energy would contribute to multiple resonance,45 and according to the exchange resonance mode, the exchange resonance frequency is given by $\omega/\gamma_0 = C\mu_{kn}^2/R_2M_s + H_z$, where C is the exchange constant (fcc-Co, 6.6 \times 10⁻¹¹ J m⁻³, hcp-Co, 6 \times 10^{-11} J m⁻³), *R* is the radius of the sphere particles, *H_z* is the applied dc field. The eigen values μ_{kn} are the roots of the equation, $[dj_n(\mu_{kn}r/R)/dr]_{r=R} = 0$, with j_n the spherical Bessel functions. The three first μ_{kn} roots are $\mu_{11} = 2.08$; $\mu_{12} = 3.34$; $\mu_{13} = 4.51$. Further, the exchange energy has been evidenced to be important for nanocrystalline alloy particles,45 and we therefore assumes that the exchange resonance mode is suitable for our cobalt particle case. Table 2 shows the resonance parameters of the cobalt superstructure are comparison to the other magnetic materials in earlier reported literatures. It has been demonstrated that the resonance frequency of magnetic materials in GHz range is determined by particle size, particle morphology and the composition of the magnetic particles. Anyhow, the coexisting of the magnetic resonance, including natural resonance and exchange resonance, is beneficial to widen the bandwidth of microwave absorption.



Fig. 7 Frequency dependence of electromagnetic parameters of cobalt particles in the range of 1–18 GHz. (a) Permittivity and dielectric loss; (b) permeability and magnetic loss.



Fig. 8 Frequency dependence of $\mu''(\mu')^{-2}f^{-1}$ of cobalt particles in the range of 1–18 GHz.

 Table 2
 The comparison of resonance parameters of cobalt superstructure with other reported magnetic particles

Materials	$f_{\rm nat}$ (GHz)	$f_{\mathrm{exch-1}}$ (GHz)	$f_{\mathrm{exch-2}}\left(\mathrm{GHz}\right)$	Reference
FeCoNi flake	7.91	14.87	—	46
FeCo nanoplates	4.80	15.26	—	47
Ni nanocone	4.40	12.00	—	48
Co nanoplatelets	3.30	11.60	—	49
Co nanochains	12.30	14.50	—	50
Co nanoflakes	5.74	7.79	12.00	41
Co particles	5.73	11.60	15.26	This work

It is well known that to obtain the materials with high-efficient microwave absorption, two problems must be focused on: impedance matching between air and absorbent, attenuation in the interior of absorbent. To meet the impedance matching, the permittivity should be equal to permeability, *i.e.* $\varepsilon' = \mu', \varepsilon'' = \mu''$. However, for the magnetic metallic materials, the real part of permeability is smaller than that of permittivity. Therefore, the real part of permittivity decreases to satisfy the impedance matching. The high attenuation in the interior of absorbent needs higher dielectric and magnetic loss. In a word, tailoring the electromagnetic parameters of the magnetic materials is necessary to achieve superior microwave absorption. In the present case, the superior microwave absorption of the cobalt particles is due to the optimized electromagnetic parameters. No doubt that the multiple dielectric and magnetic resonance is beneficial to widen the microwave absorption bandwidth.

4 Conclusions

In summary, the cobalt particles with hierarchic sword-like structure were synthesized through the liquid reduction method. Multiple dielectric and magnetic resonance peaks were exhibited in the microwave range of 1–18 GHz due to atomic and electronic polarization. One natural resonance and two exchange resonance were obtained, contributing to widen the effective microwave absorption bandwidth. A maximum reflection loss of -60.13 dB at 13.72 GHz for cobalt particles was obtained with a thickness of 1.4 mm, and the effective absorption bandwidth (RL ≤ -10 dB) is 5.42 GHz, indicating the cobalt

particles have potential application as candidate for microwave absorption.

References

- 1 J. Liu, J. Cheng, R. Che, J. Xu, M. Liu and Z. Liu, *ACS Appl. Mater. Interfaces*, 2013, 5, 2503–2509.
- 2 Y. Tang, Y. Shao, K. Yao and Y. Zhong, *Nanotechnology*, 2014, 25, 035704.
- 3 L.-S. Fu, J.-T. Jiang, L. Zhen and W.-Z. Shao, *Mater. Sci. Eng.*, *B*, 2013, **178**, 225–230.
- 4 H. Qin, Q. Liao, G. Zhang, Y. Huang and Y. Zhang, *Appl. Surf. Sci.*, 2013, **286**, 7–11.
- 5 C. Yin, Y. Cao, J. Fan, L. Bai, F. Ding and F. Yuan, *Appl. Surf. Sci.*, 2013, **270**, 432–438.
- 6 A. Porch, D. Slocombe and P. P. Edwards, *Phys. Chem. Chem. Phys.*, 2013, **15**, 2757–2763.
- 7 J. Snoek, Physica, 1948, 14, 207-217.
- 8 O. Acher and S. Dubourg, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2008, 77, 104440.
- 9 P. Toneguzzo, G. Viau, O. Acher, F. Fiévet-Vincent and F. Fiévet, *Adv. Mater.*, 1998, **10**, 1032–1035.
- 10 S.-S. Kim, S.-T. Kim, Y.-C. Yoon and K.-S. Lee, *J. Appl. Phys.*, 2005, **97**, 10F905.
- 11 L. Wu, J. Ding, H. Jiang, C. Neo, L. Chen and C. Ong, *J. Appl. Phys.*, 2006, **99**, 083905.
- 12 X. Zhang, X. Dong, H. Huang, Y. Liu, W. Wang, X. Zhu, B. Lv, J. Lei and C. Lee, *Appl. Phys. Lett.*, 2006, **89**, 053115.
- 13 X. F. Zhang, X. L. Dong, H. Huang, B. Lv, J. P. Lei and C. J. Choi, *J. Phys. D: Appl. Phys.*, 2007, **40**, 5383–5387.
- 14 L. Yan, J. Wang, X. Han, Y. Ren, Q. Liu and F. Li, *Nanotechnology*, 2010, 21, 095708.
- 15 Z. Ma, J. Wang, Q. Liu and J. Yuan, *Appl. Surf. Sci.*, 2009, 255, 6629–6633.
- 16 F. Wen, F. Zhang and Z. Liu, J. Phys. Chem. C, 2011, 115, 14025–14030.
- 17 G. Tong, J. Yuan, W. Wu, Q. Hu, H. Qian, L. Li and J. Shen, *CrystEngComm*, 2012, **14**, 2071–2079.
- 18 L. Guo, F. Liang, N. Wang, D. Kong, S. Wang, L. He, C. Chen, X. Meng and Z. Wu, *Chem. Mater.*, 2008, **20**, 5163–5168.
- 19 L.-P. Zhu, H.-M. Xiao, W.-D. Zhang, G. Yang and S.-Y. Fu, *Cryst. Growth Des.*, 2008, **8**, 957–963.
- 20 G. Dumpich, T. Krome and B. Hausmanns, J. Magn. Magn. Mater., 2002, 248, 241–247.
- 21 J. B. Tracy, D. N. Weiss, D. P. Dinega and M. G. Bawendi, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2005, **72**, 064404.
- 22 S. Chikazumi and S. H. Charap, *Physics of magnetism*, RE Krieger Publishing Company, Malabar, FL, 1978.
- 23 Y.-J. Zhang, Q. Yao, Y. Zhang, T.-Y. Cui, D. Li, W. Liu, W. Lawrence and Z.-D. Zhang, *Cryst. Growth Des.*, 2008, 8, 3206–3212.
- 24 I. Jacobs and C. Bean, Phys. Rev., 1955, 100, 1060.
- 25 W. Zhou, K. Zheng, L. He, R. Wang, L. Guo, C. Chen, X. Han and Z. Zhang, *Nano Lett.*, 2008, **8**, 1147–1152.
- 26 J. Sort, J. Nogués, S. Suriñach, J. Muñoz and M. Baró, *Mater. Sci. Eng.*, A, 2004, 375, 869–873.

- 27 E. Michielssen, J.-M. Sajer, S. Ranjithan and R. Mittra, *IEEE Trans. Microwave Theory Tech.*, 1993, **41**, 1024–1031.
- 28 M. Zhou, X. Zhang, J. Wei, S. Zhao, L. Wang and B. Feng, J. Phys. Chem. C, 2010, 115, 1398–1402.
- 29 S. Sugimoto, T. Maeda, D. Book, T. Kagotani, K. Inomata, M. Homma, H. Ota, Y. Houjou and R. Sato, *J. Alloys Compd.*, 2002, **330–332**, 301–306.
- 30 J. R. Liu, M. Itoh and K.-i. Machida, *Chem. Lett.*, 2003, 394– 395.
- 31 W. Yang, L. Qiao, J. Wei, Z. Zhang, T. Wang and F. Li, *J. Appl. Phys.*, 2010, **107**, 033913.
- 32 Q. Liu, D. Zhang and T. Fan, Appl. Phys. Lett., 2008, 93, 013110-013110-3.
- 33 Z. Li, B. Shen, Y. Deng, L. Liu and W. Hu, *Appl. Surf. Sci.*, 2009, **255**, 4542–4546.
- 34 Z. Li, Y. Deng, B. Shen and W. Hu, *Mater. Sci. Eng.*, *B*, 2009, **164**, 112–115.
- 35 G. Bertotti, J. Appl. Phys., 1985, 57, 2110-2117.
- 36 A. Aharoni, J. Appl. Phys., 1991, 69, 7762-7764.
- 37 G. Tong, W. Wu, R. Qiao, J. Yuan, J. Guan and H. Qian, *J. Mater. Res.*, 2011, **26**, 1639.
- 38 F. Wen, H. Yi, L. Qiao, H. Zheng, D. Zhou and F. Li, *Appl. Phys. Lett.*, 2008, **92**, 042507.

- 39 M. Wu, Y. Zhang, S. Hui, T. Xiao, S. Ge, W. Hines, J. Budnick and G. Taylor, *Appl. Phys. Lett.*, 2002, **80**, 4404–4406.
- 40 C. Kittel, Phys. Rev., 1948, 73, 155.
- 41 F. Ma, Y. Qin and Y.-Z. Li, Appl. Phys. Lett., 2010, 96, 202507.
- 42 X. Liu, M. M. Steiner, R. Sooryakumar, G. A. Prinz, R. F. C. Farrow and G. Harp, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, 53, 12166–12172.
- 43 R. Ramprasad, P. Zurcher, M. Petras, M. Miller and P. Renaud, *J. Appl. Phys.*, 2004, **96**, 519–529.
- 44 K. Rozanov, Z. Li, L. Chen and M. Koledintseva, *J. Appl. Phys.*, 2005, **97**, 013905.
- 45 W. Zhong, C. Q. Sun, S. Li, H. Bai and E. Jiang, *Acta Mater.*, 2005, **53**, 3207–3214.
- 46 L. J. Deng, P. H. Zhou, J. L. Xie and L. Zhang, *J. Appl. Phys.*, 2007, **101**.
- 47 Y. Yang, C. Xu, Y. Xia, T. Wang and F. Li, *J. Alloys Compd.*, 2010, **493**, 549–552.
- 48 F. Ma, Y. Qin, F. Wang and D. Xue, Scr. Mater., 2010, 63, 1145–1148.
- 49 J. Li, J. Huang, Y. Qin and F. Ma, *Mater. Sci. Eng.*, *B*, 2007, **138**, 199–204.
- 50 X.-L. Shi, M.-S. Cao, J. Yuan and X.-Y. Fang, *Appl. Phys. Lett.*, 2009, **95**, 163108.