

Contents lists available at ScienceDirect

### Catalysis Communications



journal homepage: www.elsevier.com/locate/catcom

#### Short Communication

# Synthesis of cyclic carbonate from epoxide and CO<sub>2</sub> catalyzed by magnetic nanoparticle-supported porphyrin

#### Dongsheng Bai, Qiong Wang, Yingying Song, Bo Li, Huanwang Jing\*

State Key Laboratory of Applied Organic Chemistry, College of Chemistry and Chemical Engineering, Lanzhou University, 222 South Tianshui Road, Lanzhou, Gansu 730000, PR China

#### ARTICLE INFO

#### ABSTRACT

Article history: Received 3 October 2010 Received in revised form 14 December 2010 Accepted 16 December 2010 Available online 23 December 2010

Keywords: Epoxide Cyclic carbonate Coupling reaction Magnetic nanoparticle Supported porphyrin

#### 1. Introduction

The chemistry of carbon dioxide has received much attention in decades from both economical and environmental points of view: utilization of the least-expensive carbon source and reduction of global-warming gas [1]. One of the most successful examples is the synthesis of cyclic carbonates from CO<sub>2</sub> and epoxides. The cyclic carbonates have been widely used as synthetic intermediates, aprotic polar solvents, precursors for biomedical applications and raw materials for engineering plastics [2–16]. Various catalysts including alkali metal salts, Lewis acids, transition metal complexes, ionic liquids and organometallic compounds, have been developed for the coupling reaction of epoxide and carbon dioxide to yield cyclic carbonate in recent years [17–24]. However, those homogeneous catalysts have obvious drawbacks of recovery and reutilization. Hence, the immobilization of homogeneous catalysts, especially biomimetic catalysts such as metalloprophyrins, is much desired.

For fixing our biomimetic catalyst of metalloporphyrin, we have recently regarded that the catalysts supported by the Fe<sub>3</sub>O<sub>4</sub> magnetic nanoparticle have been developed and used in various reactions [25–32] due to their superparamagnetism property, large surface area to volume ratios that is easy to be functionalized [33]. In this paper, the Fe<sub>3</sub>O<sub>4</sub> magnetic nanoparticle-supported porphyrinato cobalt<sup>III</sup> (MNP-P) has been designed, synthesized (Scheme 1) and evaluated as a recoverable catalyst for coupling reaction of epoxide and CO<sub>2</sub> (Scheme 2). The greatest advantage of magnetic nanoparticle-supported porphyrin

could be simply recycled and reused for 16 times without significant loss of activity.

© 2010 Elsevier B.V. All rights reserved.

#### 2. Experimental

magnet and reused for 16 times without significant loss of activity and mass.

#### 2.1. Materials and instrumentations

A magnetic nanoparticle (MNP)-supported biomimetic cobalt porphyrin as cytochrome P-450 model was

designed, prepared and evaluated as an efficient catalyst for coupling reaction of epoxide and CO2 under

1.0 MPa CO<sub>2</sub> pressure at ambient temperature to generate relevant cyclic carbonate with excellent selectivity

in high yield. The supported porphyrin catalyst could be simply recycled with the assistance of an external

Propylene oxide (PO), epichlorohydrin, 1,2-epoxybutane, 1,2-epoxydodecane and 1,2-epoxy-3-phenoxypropane were purchased from Aldrich. Styrene oxide and cyclohexene oxide were obtained from Alfa Aesar. Oxirane was obtained from Beijing Chemical Reagent Corporation. Tetrabutylammonium fluoride (TBAF), tetrabutylammonium chloride (TBAC), tetrabutylammonium bromide (TBAB), tetrabutylammonium iodide (TBAI) and phenyltrimethylammonium tribromide (PTAT) were purchased from Na–K alloy. Propylene oxide and *n*-hexane were distilled from CaH<sub>2</sub>. Other epoxides were used to the reaction without further purification unless otherwise indicated.

Infrared spectra were collected on a Nicolet NEXUS 670 FT-IR spectrometer using a KBr pallet. ICP data were evaluated on an inductively coupled plasma atomic emission spectrometer of Thermo Fisher Scientific CP-IRIS Advantage. TEM was obtained using a JEOL JEM-2010 F transmission electron microscope (operated at 200 kV). The variable temperature magnetic susceptibility data of complex were recorded on SQUID magnetometer using the polycrystalline sample in the range of 300 to 2 K. The XRD patterns were acquired on Bruker SMART APEX II X-ray diffractometer. GC analyses of cyclic carbonates were carried out on a Varian CP-3800 gas chromatograph equipped with FID detectors.

<sup>\*</sup> Corresponding author. Tel.: +86 931 891 2585; fax: +86 931 891 2582. *E-mail address:* jing-hw@163.com (H. Jing).

<sup>1566-7367/\$ –</sup> see front matter 0 2010 Elsevier B.V. All rights reserved. doi:10.1016/j.catcom.2010.12.024



Scheme 1. General procedure for the synthesis of MNP-P catalyst.

#### 2.2. Preparation of free-base porphyrin 1 and metalloporphyrin 2

Free-base porphyrin 5,10,15,20-tetra-*o*-aminophenylporphyrin **1** ( $H_2$ TAPP) and its cobalt<sup>III</sup> complex 5,10,15,20-tetra-*o*-aminophenylporphyrinato cobalt **2** (Co<sup>III</sup>TAPP) were synthesized, purified and characterized following the procedures of literature [22].

#### 2.3. Preparation of functionalized cobalt porphyrin 3

3-Isocyanatopropyltriethoxysilane (0.1 ml, 0.4 mmol) was added to a solution of metalloporphyrin **2** (79 mg, 0.1 mmol) in toluene (10 ml). The mixture was stirred for 12 h at 85 °C. After cooling to room temperature, the reaction mixture was concentrated under reduced pressure. The obtained solid was washed with hexane for three times and dried in vacuum to generate functionalized cobalt porphyrin **3** 165 mg (93% yield) as a purple solid.

Characterization of porphyrin **3**: <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta = 0.82$  (m, 8H; CH<sub>2</sub>), 0.96 (t, J = 9.0 Hz, 36H; CH<sub>3</sub>), 1.38 (m, 8H; CH<sub>2</sub>), 2.49 (m, 8H; CH<sub>2</sub>), 3.5 (m, 24H; CH<sub>2</sub>), 3.82 (s, 3H; CH<sub>3</sub>), 4.70 (s, 8H; NH), 7.41 (m, 4H;  $\beta$ -pyrrole H), 7.74 (m, 4H;  $\beta$ -pyrrole H), 7.94 (m, 4H; *o*-aryl H), 8.28 (m, 4H; *p*-aryl H), 8.76 (m, 8H; *m*-aryl H); <sup>13</sup>C NMR (300 MHz, CDCl<sub>3</sub>)  $\delta = 8.38$ , 19.3, 24.3, 43.6, 55.8, 60.2, 116.5, 120.0, 123.0, 130.9, 132.7, 135.2, 135.6, 140.3, 141.0, 151.0, 156.0, and 156.7. Anal. Calcd for C<sub>86</sub>H<sub>119</sub>N<sub>12</sub>O<sub>18</sub>Si<sub>4</sub>Co: C, 58.02; H, 6.74; N, 9.44. Found: C, 57.86; H, 6.88; N, 9.18. IR (cm<sup>-1</sup>) 3350.1 ( $\nu$ <sub>N-H</sub>, m, br), 3060.6 ( $\nu$ <sub>Ar-H</sub>, w), 2970.1 (m), 2923.8 (m), 2880.9 ( $\nu$ <sub>C-H</sub>, m), 1667.5 ( $\nu$ <sub>C o</sub>, s), 1580.0 (w), 1521.2 (vs), 1441.9 ( $\nu$ <sub>Ar</sub>, s), 1073.9 ( $\nu$ <sub>Si-O</sub>, vs), 999.6 ( $\nu$ <sub>Si-C</sub>, s), and 756.0 ( $\nu$ <sub>Ar-H</sub>, bending, m).



Scheme 2. Coupling reaction catalyzed by MNP-P/PTAT.

2.4. Synthesis of  $Fe_3O_4$  superparamagnetic nanoparticles and  $Fe_3O_4$  supported cobalt porphyrin **4** 

Magnetic nanoparticles of  $Fe_3O_4$  were prepared following the procedure of literature [34].  $Fe(acac)_3$  (0.706 g, 2 mmol) was added to a mixture of benzyl ether (10 ml) and oleylamine (10 ml) in a round-bottom flask. The above solution was heated to 110 °C and kept for 1 h under nitrogen, then quickly heated to 300 °C and maintained at this temperature for 2 h. A black-brown mixture was obtained and cooled to room temperature. The mixture was washed with ethanol (40 ml) and the precipitate was collected by centrifugation at 8000 rpm. Finally, the product was redispersed in hexane. The transmission electron microscope (TEM) of  $Fe_3O_4$  demonstrates that the average diameter of this magnetic  $Fe_3O_4$  nanoparticles were 5–8 nm (Fig. 1a). The XRD patterns and magnetic curves were shown in Fig. 1b and Fig. 1c respectively.

The general procedure for synthesis of MNP-P catalyst was shown in Scheme 1. A mixture of MNP (96 mg, 0.42 mmol), cobalt porphyrin **3** (178 mg, 0.1 mmol) and anhydrous toluene (20 ml) was ultra-sonicated for 2 min and then heated to reflux for 12 h. After cooling to room temperature, the reaction mixture was separated by decantation using an external magnet and washed with  $CH_2Cl_2$  (3 ml×3) to obtain a darkbrown powder **4**. The quantity of metalloporphyrin catalyst coating was 0.4966 mmol/g determined by ICP. TEM, XRD and magnetic curve of reused MNP-P were shown in Fig. 1 a1, b1 and c1. IR (cm<sup>-1</sup>) of MNP-P: 3378.5 ( $v_{N-H}$ , m, br), 3060.6 ( $v_{Ar-H}$ , w), 2997.5 (w), 2923.1 (s), 2854.6 ( $v_{C-H}$ , w), 1641.8 ( $v_{CO}$ , m), 1580.0 (sh), 1549.2 (m), 1529.9 (m), 1442.7 ( $v_{Ar}$ , s), 1073.9 ( $v_{SI-O}$ , vs), 1002.2 ( $v_{SI-C}$ , s), 756.1 ( $v_{Ar-H}$ , bending, m).

#### 2.5. General procedure for synthesis of cyclic carbonates

All coupling reactions were carried out in a 100 ml stainless steel autoclave equipped with a 10 ml glass tube. The tube in the autoclave was equipped with a stir bar and charged with MNP-P (43 mg), Lewis base (0.08 mmol) and epoxide (15 mmol) without additional solvent unless otherwise indicated. The autoclave was pressurized with  $CO_2$ to 1.0 MPa and then stirred at room temperature. After a proper time, when the pressure fell down to 0.7 MPa, the reactor was vented. The



**Fig. 1.** a) The TEM image of Fe<sub>3</sub>O<sub>4</sub> nanoparticles (a), MNP-P (a1), recovery MNP-P (a2); The XRD patterns of Fe<sub>3</sub>O<sub>4</sub> nanoparticles (b), MNP-P (b1), recovery MNP-P (b2); The magnetic curve of Fe<sub>3</sub>O<sub>4</sub> nanoparticles (c), MNP-P (c1), recovery MNP-P (c2).

remaining mixture was dissolved in 1 ml  $CH_2Cl_2$ . The catalyst MNP-P was separated by an external magnet (Fig. 2. b). After distillation of unreacted epoxide and solvent at room temperature, the residue was then distilled under reduced pressure at about 90 °C to give a pure cyclic carbonate as a colorless liquid, or a solid product that was recrystallized with ethanol to obtain the pure cyclic carbonate.

#### 2.6. Recycling procedure of MNP-P catalyst

Dichloromethane was added to dilute the reaction mixture after terminating the reaction. The catalyst of MNP-P was quickly subsided to the bottom of the reaction tube when an external magnet was used. Then, the obtained liquid containing the cyclic carbonate can be easily decanted. The recovery MNP-P was washed with  $CH_2Cl_2$  (3 ml) and epoxide (3 ml) for five times respectively, then reused directly to the next run with another portion of co-catalyst of PTAT. TEM, XRD and magnetic curve of reused MNP-P were shown in Fig. 1 a2, b2 and c2.

#### 3. Results and discussion

## 3.1. Co-catalyst effect on the synthesis of propylene carbonate from propylene oxide and $\mathrm{CO}_2$

The MNP-P was used as catalyst and quaternary ammonium salt was used as co-catalyst in the model reaction of propylene oxide and  $CO_2$ . As shown in Table 1, the reaction took place smoothly in the presence of catalysts affording the desired propylene carbonate (PC) in high yield. The use of PTAT was shown to accelerate the reaction (Table 1, entries 1–3 vs. 7) and the activity of catalytic system increased with higher PTAT loading (Table 1, entries 5–8). The tetrabutylammonium iodide almost



Fig. 2. a) The MNP-P was dispersed in PO; b) The MNP-P was separated with an external magnet.

Table 1

Synthesis of cyclic carbonate from propylene oxide (PO) and CO<sub>2</sub> catalyzed by MNP-P<sup>a</sup>.

Entry	Catalyst	Co-catalyst/mmol	Reaction time (h)	Yield (%) <sup>b</sup>
1	MNP-P	TBAF/0.08	24	26.9
2	MNP-P	TBAC/0.08	24	35.2
3	MNP-P	TBAB/0.08	24	74.5
4	MNP-P	TBAI/0.08	24	97.9
5	MNP-P	PTAT/0.02	24	38.6
6	MNP-P	PTAT/0.04	24	93.1
7	MNP-P	PTAT/0.08	24	97.2
8	MNP-P	PTAT/0.16	16	93.1
9 <sup>c</sup>	-	PTAT/0.08	24	21.4
10 <sup>d</sup>	MNPs	-	24	-
11 <sup>d</sup>	MNP-P	-	24	-
12 <sup>e</sup>	Co(TAPP)(OAc)	PTAT/0.08	10	88.3

<sup>a</sup> Reaction conditions: PO, 15 mmol; MNP-P, 43 mg; CO<sub>2</sub> pressure, 1.0 MPa; 25 °C.
 <sup>b</sup> Isolated yield, the selectivity determined by GC>99.9%.

<sup>c</sup> Without MNP-P.

<sup>d</sup> When MNPs or MNP-P was used only as catalyst, no reaction was occurred.

<sup>e</sup> Catalyst Co(TAPP)(OAc) catalyst, 16 mg.

has the same superior activity as PTAT due to the higher nucleophilicity of iodide ion (Table 1, entry 4 vs. 7). Although the propylene carbonate can be obtained with the using of PTAT only (Table 1, entry 9), the addition of MNP-P significantly accelerated this coupling reaction (Table 1, entries 1–8). The activity of the MNP-P catalyst in terms of accompanied cocatalyst is in the order of PTAT>TBAI>TBAC>TBAF. This result was consistent with the literature report [13].

#### 3.2. Recycling of MNP-P catalyst

Since the metalloporphyrins used as catalysts are highly expensive materials, the recovery and reuse are the key factors which limit their applications in synthetic chemistry and industrial processes. The recycling of MNP-P catalyst was then investigated. The product separation and the recycling of the biomimetic catalyst MNP-P were indeed quite easy and simple using an external magnet (Fig. 2a, b). When the yield of PC was dropped down for 3% (Fig. 3, entries 1, 4, 6, 10, 13 and 15), the MNP-P catalyst needed to be reoxidized in 5 ml CH<sub>2</sub>Cl<sub>2</sub> with extra addition of 0.1 ml acetic acid in an open flask for five hours or in a dioxygen atmosphere for one hour in order to recover its catalytic activity, then washed with  $CH_2Cl_2$  and PO for five times (3 ml × 5) respectively, and then reused directly to the next run. The catalyst can be recycled for 16 times in this manner (Fig. 3) without significantly loss of activity. Then the recovery catalyst of MNP-P was washed and dried in vacuum. The weight of it was still 43 mg.



Fig. 3. Recycling of MNP-P catalyst. Reaction conditions: PO, 15 mmol; MNP-P, 43 mg; PTAT, 0.08 mmol;  $CO_2$ , 1.0 MPa; time, 24H; temperature 25 °C.

The IR spectra of recovery catalyst showed the same peaks as the new MNP-P catalyst. Hence, there was no leaching of porphyrin from the support during the reaction. From the measurements of TEM of recovery catalyst (Fig. 1, a2), we can see that the diameters of catalyst were the same size compared with the fresh catalyst (Fig. 1, a1) and the precursor (Fig. 1a). Comparing the XRD patterns of reused catalyst (Fig. 1, b2) with that of fresh catalyst (Fig. 1, b1) and Fe<sub>3</sub>O<sub>4</sub> (Fig. 1b), the crystal lattice of catalyst was not changed; The magnetic curves of MNP-P (Fig. 1. c1) showed a decrease after coating the porphyrin **3** to Fe<sub>3</sub>O<sub>4</sub> nanoparticles due to the diamagnetism of organic groups, and the magnetic curves of reused MNP-P (Fig. 1 c2) was decreased again after 16 recycles that did not influence their recyclability.

#### 3.3. Cycloaddition of various epoxides with CO<sub>2</sub>

Under the optimized reaction condition, the scope of substrates was then extended using MNP-P as catalyst (Table 2). As shown in Table 2, MNP-P/PTAT catalytic system can initiate the coupling reaction of a number of epoxides and  $CO_2$  to generate the corresponding cyclic carbonates in high yield (Table 2, entries 1, 2, 3 and 7). The coupling reaction of styrene oxide (Table 2, entry 6) and phenoxypropylene oxide (Table 2, entry 7) and  $CO_2$  must be performed with dilute solvent of  $CH_2Cl_2$  respectively due to their corresponding cyclic carbonates are solids. This catalytic system can

#### Table 2

The coupling results of various epoxides and CO2 catalyzed by MNP-P/PTAT<sup>a</sup>.

Entry	Reactant	Product	Reaction time (h)	Yield (%) <sup>b</sup>
1	$\wedge$		24	97.6
2			24	97.2
3	CI	CI	24	93.1
4	$\checkmark$	° V O	36	52.4
5c	M <sub>9</sub>		24	44.2
6 <sup>c</sup>	Ph	O O Ph	36	48.7
7 <sup>c</sup>	Ph <sup>-0</sup>	Ph <sup>-0</sup>	24	91.7
8	o		48	8.9

 $<sup>^{\</sup>rm a}$  Reaction conditions: epoxide, 15 mmol; MNP-P, 43 mg; PTAT, 0.08 mmol; CO\_2 1.0 MPa; 25 °C.

<sup>c</sup> CH<sub>2</sub>Cl<sub>2</sub>, 1 ml.

<sup>&</sup>lt;sup>b</sup> Isolated yield, the selectivity determined by GC>99.9%.

also be realized in the coupling reaction of cyclohexene oxide (CHO) and  $CO_2$  to obtain the cyclohexene carbonate (8.9%, Table 2, entry 8) that is difficult to get in many catalyst systems. To estimate the purity of cyclic carbonates, the IR spectroscopy was used and gave only one peak at around 1795 cm<sup>-1</sup> attributed to the carbonyl group in cyclic carbonate. However, the peak of 1749 cm<sup>-1</sup> was not detected, which was attributed to the carbonyl group in polycarbonate [35]. The gas chromatography technology was used to detect the impurities. The GC traces showed that there was no other by-product.

#### 4. Conclusions

In summary, we have synthesized a new MNPs-supported biomimetic cobalt porphyrin as an efficient and recyclable catalyst for the coupling reaction of epoxides and CO<sub>2</sub> to generate relevant cyclic carbonate with excellent selectivity in high yield. The product separation and catalyst recycling are concise using an external magnet. The MNP-P catalyst can be recovered and reused up to 16 times without significant loss of activity and mass.

#### Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC 20973086). We are grateful to Professor Wei Wang for help with the material of magnetic nanoparticles, TEM and magnetic measurements.

#### References

- D.J. Darensbourg, R.M. Mackiewicz, A.L. Phelps, D.R. Billodeaux, Acc. Chem. Res. 37 (2004) 836–844.
- [2] W. Yamada, Y. Kitaichi, H. Tanaka, T. Kojima, M. Sato, T. Ikeno, T. Yamada, Bull. Chem. Soc. Jpn 80 (2007) 1391–1401.
- [3] R.L. Paddock, S.T. Nguyen, J. Am. Chem. Soc. 123 (2001) 11498–11499.
- [4] M. Aresta, A. Dibenedetto, L. Gianfrate, C. Pastore, J. Mol, Catal. A Chem. 204–205 (2003) 245–252.

- [5] W.N. Sit, S.M. Ng, K.Y. Kwong, C.P. Lau, J. Org. Chem. 70 (2005) 8583-8586.
- [6] A. Berkessel, M. Brandenburg, Org. Lett. 8 (2006) 4401-4404.
- [7] H.S. Kim, J.J. Kim, S.D. Lee, M.S. Lah, D. Moon, H.G. Jang, Eur. Chem. J. 9 (2003) 678-686.
- [8] K.C. Nicolaou, Z. Yang, J.J. Liu, H. Ueno, P.G. Nantermet, R.K. Guy, C.F. Claiborne, J. Renaud, E.A. Couladouros, K. Paulvannan, E.J. Sorensen, Nature 367 (1994) 630–634.
- [9] T. Takata, Y. Furusho, K.-I. Murakawa, T. Endo, H. Matsuoka, T. Hirasa, J. Matsuo, M. Sisido, J. Am. Chem. Soc. 120 (1998) 4530–4531.
- [10] H.T. Chang, K.B. Sharpless, Tetrahedron Lett. 37 (1996) 3219-3222.
- [11] H. Jing, S.T. Nguyen, J. Mol, Catal. A Chem. 261 (2007) 12-15.
- [12] J.M. Sun, S.I. Fujita, F.Y. Zhao, M. Arai, Green Chem. 6 (2004) 613–616.
  [13] X.-B. Lu, B. Liang, Y.J. Zhang, Y.Z. Tian, Y.M. Wang, C.X. Bai, H. Wang, R. Zhang, J.
- Am. Chem. Soc. 126 (2004) 3732–3733.
  Y. Xie, Z.F. Zhang, T. Jiang, J.H. He, B.X. Han, T.B. Wu, K.L. Ding, Angew. Chem. Int. Ed. 46 (2007) 7255–7258.
- [15] S.L. Zhang, Y.Z. Huang, H.W. Jing, W.X. Yao, P. Yan, Green Chem. 11 (2009) 935–938.
- [16] T. Chang, L.L. Jin, H.W. Jing, ChemCatChem 1 (2009) 379-783.
- [17] P. Yan, H.W. Jing, Adv. Synth. Catal. 351 (2009) 1325–1332.
- [18] W.J. Kruper, D.V. Dellar, J. Org. Chem. 60 (1995) 725-727.
- [19] H. Sugimoto, T. Kimura, S. Inoue, J. Am. Chem. Soc. 121 (1999) 2325–2326.
  [20] R.L. Paddock, Y. Hiyama, J.M. McKay, S.T. Nguyen, Tetrahedron Lett. 45 (2004)
- 2023–2026. [21] R. Srivastava, T.H. Bennur, D. Srinivas, J. Mol, Catal. A Chem. 226 (2005) 199–205.
- [22] L.L. Jin, H.W. Jing, T. Chang, X.L. Bu, L. Wang, Z.L. Liu, J. Mol, Catal. A Chem. 261 (2007) 262–266.
- [23] D.S. Bai, X.X. Wang, Y.Y. Song, B. Li, L.L. Zhang, P. Yan, H.W. Jing, Chin. J. Catal. 31 (2010) 51–59.
- [24] V. Caló, A. Nacci, A. Monopoli, A. Fanizzi, Org. Lett. 4 (2002) 2561-2563.
- [25] A. Hu, G.T. Yee, W. Lin, J. Am. Chem. Soc. 127 (2005) 12486–12487.
- [26] S. Ko, J. Jang, Angew. Chem. Int. Ed. 45 (2006) 7564–7567.
- [27] M. Kawamura, K. Sato, Chem. Commun. (2006) 4718-4719.
- [28] G. Chouhan, D. Wang, H. Alper, Chem. Commun. (2007) 4809-4811.
- [29] M. Shokouhimehr, Y. Piao, J. Kim, Y. Jang, T. Hyeon, Angew. Chem. Int. Ed. 46 (2007) 7039–7043.
- [30] R. Abu-Reziq, D. Wang, M.L. Post, H. Alper, Chem. Mater. 20 (2008) 2544-2550.
- [31] V. Polshettiwar, R.S. Varma, Chem. Eur. J. 15 (2009) 1582–1586.
- [32] X.X. Zheng, S.Z. Luo, L. Zhang, J.-P. Cheng, Green Chem. 11 (2009) 455-458.
- [33] A. Hu, G.T. Yee, W. Lin, J. Am. Chem. Soc. 127 (2005) 12486-12487.
- [34] Z.C. Xu, C.M. Shen, Y.L. Hou, H.J. Gao, S.H. Sun, Chem. Mater. 21 (2009) 1778–1780.
- [35] Y.S. Niu, W.X. Zhang, H.C. Li, X.S. Chen, J.R. Sun, X.L. Zhuang, X.B. Jing, Polymer 50 (2009) 441–446.