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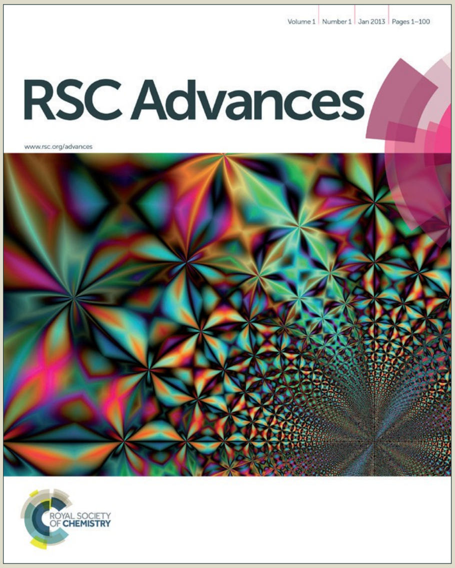

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ARTICLE

Converting urea into high value-added 2-oxazolidinones under solvent-free conditions

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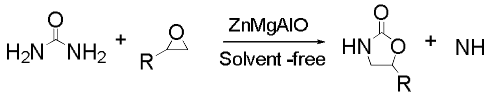
Zn-modified mesoporous Mg–Al nanoplates oxides were prepared by co-precipitation method, characterized and used in the synthesis of 2-oxazolidinones from urea and epoxides under solvent-free conditions. The characterization results suggested that $Zn_{1.1}Mg_{2.0}AlO_{4.6}$ with more accessible active medium basic sites were favorable for obtaining much superior catalytic activity. This synthetic process is mild, convenient, simple and gives good yields to 80%.

1. Introduction

Carbon dioxide (CO_2) is an abundant, renewable and economical carbon resource, so the direct use of CO_2 as a raw material in chemical industry should be an ideal choice.[1-4] However, carbon atom in CO_2 is in its most oxidized form and is a relatively unreactive molecule, therefore, the activation of CO_2 normally needs the usage of a highly energy starting materials or to shift the equilibrium to the right by removing a compound.[5-6] The use of urea as an active form of carbon dioxide is a feasible way in the chemical industry. Until now, manufacturing urea is very mature[7-9] and currently supply of urea in China is exceeding demand. In this sense, using urea as feedstock to produce higher valuable chemicals opens a new window for CO_2 utilization. This easily accessible chemical has been used as building block in the synthesis of N-carbamoyl-L-amino acids,[10] carbamates,[11-14] cyclic carbonates or dialkyl carbonates,[11-13] diphenyl carbonate,[15-16] urea derivatives[17-18] and many nitrogen-containing heterocycles.[19-26] Green chemistry can be defined as the synthesis of important chemical and biological products from readily available and inexpensive starting materials through atom economical and environmentally benign strategies. In this work, urea was used for the synthesis of 2-oxazolidinones (Scheme 1), which are important cyclic compounds in both fine chemicals and synthetic organic chemistry. They are widely used in the synthesis of pharmaceuticals, pesticides, cosmetics, and so on.[27-29] From economical and environmental views, the direct synthesis of 2-oxazolidinones from CO_2 and aziridines[30-33] or β-aminoalcohols[34-36] is more attractive. Nevertheless, most of these works require high pressure or high temperature or some stoichiometric dehydrating reagents. To the best of our knowledge, little work appears to have been done on the reaction of urea and epoxides, and the reaction could be carried out without any solvent. In such process, urea can be used as the carbonylation and amination agent, which is a nontoxic material and has abundant resources with lower price. Meanwhile, NH_3 co-produced in the reaction can be easily converted to urea, since the urea synthesis from CO_2 and NH_3 has been established. Hence, this route could be considered as indirect utilization of CO_2 to produce the green chemicals of 2-oxazolidinones.

In this study, Zn-modified mesoporous Mg–Al mixed oxides were prepared by calcinations of Zn-Mg-Al hydrotalcite-like compounds, which were found to catalyze the 2-oxazolidinones synthesis from urea and epoxides with high efficiency. TG, XRD, BET, SEM and CO_2-TPD studies were conducted to explore the relationship between structure and performance.



Scheme 1 Synthesis of 2-oxazolidinones from urea and epoxides.

2. Experimental

2.1 Catalysts preparation and characterization

The Mg-Zn-Al hydrotalcites (HTMg–Zn–Al) were prepared by co-precipitation method (See supporting information).[13] Elemental quantitative analyses of Mg, Zn and Al were performed with a CCD-based inductively coupled plasma-atomic emission spectrometer (ICP-AES, Agilent 725-ES). The morphological structures were examined by field emission scanning electron microscopy (FE-SEM, JSM-6701F). Thermal analyses were carried out using a METTLER TG1 model. X-ray diffraction (XRD) was measured on a Siemens D/max-RB powder X-ray diffract meter. The BET surface areas of the catalysts were obtained with physisorption of N_2 using a

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Micromeritics ASAP 2010. The surface base properties of the catalysts were measured by temperature programmed desorption (TPD) of CO_2 and carried out on TPD flow system equipped with a TCD detector.

2.2 2-oxazolidinones synthese from urea and epoxides

Typically, 10 mmol epoxide, 20 mmol urea and 0.05 g catalyst were added into the stainless steel autoclave with a glass tube inside. The reactions were carried out at 120-150 °C for 2-8 h with stirring. After reaction, the autoclave was cooled down to room temperature. The reaction mixture was diluted with methanol to 15 ml and then the qualitatively identified by HP-7890 GC-MS equipped with a SE-54 capillary column. The quantitative analysis of the product was determined by Agilent 7890 GC equipped with a SE-54 capillary column and a FID detector (biphenyl was used as internal standard).

3. Results and discussion

3.1 Results of the catalysts characterization

The typical TG (Fig. 1), XRD (Fig. 2) patterns demonstrated the formation of layered double hydroxides (LDHs). All the hydrotalcites showed three similar stages of weight loss in TG curves. For $HTZn_{1.1}Mg_{2.0}Al$, the first step, ranging from 50 °C to 180 °C, is due to the evaporation of surface water on the sample. In the following stage, interlayer water molecules are lost up to 381 °C. Dehydroxylation, removal of the hydroxyl groups from the layers as water vapour, and decomposition of the interlayer anions occur at higher temperatures up to 600 °C. As shown in Fig. 2, the $HTMg_{3.0}Al$ and $HTZn_{3.2}Al$ showed the typical XRD patterns of the hydrotalcite structure with intense sharp and symmetric peaks.[37] When the Zn component was introduced to the $HTMg_{3.0}Al$, the diffraction peaks of $HTZn_{1.1}Mg_{2.0}Al$ is still consisted with the peaks of HTs, demonstrating that the obtained sample kept the layered structure. However, the layered structure destroyed thoroughly in $HTZn_{1.1}Mg_{2.0}Al$ and ZnO diffraction peaks are observed after calcination. The obtained composite oxides show high specific surface areas (>100 m^2/g) owing to the formation of a significant porosity (Table 1). All of the oxides displayed a mesoporous material (the average pore size ranging from about 9 to 19 nm). Besides, the sheet-like structure can also be visualized from the SEM images (Fig. 3A), and it exhibited mainly nanoplate-shaped crystals. After calcination at 400 °C (Fig. 3B), the discriminable nanoplates-like features was still exist, suggesting that 400 °C was the appropriate treatment conditions in order to completely decompose the interlayer anions without exceeding the critical temperature at which phase segregation and sintering take place.[13]

Table 1 Physical and base properties of the composite oxides derived from HTs

Catalyst	S_{BET} (m^2/g)	D_p (nm)	V_p (cm^3/g)	Basic sites (μmol/g)[a]			
				Weak <100 °C	Medium 100-300 °C	Strong >300 °C	Total
$Mg_{3.0}AlO_{4.5}$	158	9	0.4	60	52	15	127
$Zn_{3.2}AlO_{4.7}$	103	19	0.5	15	-	-	15
$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	155	12	0.6	31	21	-	52
$Zn_{1.1}Mg_{2.0}AlO_{4.6}$-reused	-	-	-	35	10	-	45

a: Determined by ICP. B: Determined by TPD.

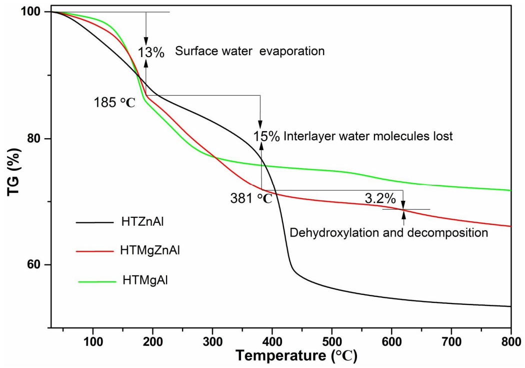

Fig. 1 TGA curve of the hydrotalcite-like compounds.

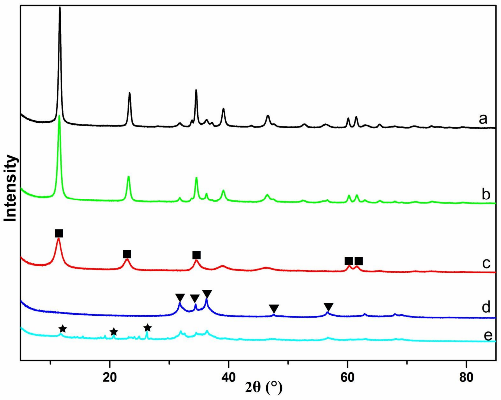

Fig. 2 XRD patterns of (a) $HTZn_{3.2}Al$; (b) $HTZn_{1.1}Mg_{2.0}Al$; (c) $HTMg_{3.0}Al$; (d) $Zn_{1.1}Mg_{2.0}AlO_{4.6}$ and (e) $Zn_{1.1}Mg_{2.0}AlO_{4.6}$-reused (■:HTs; ▼: ZnO; ★: $Zn(NH_3)_2(NCO)_2$).

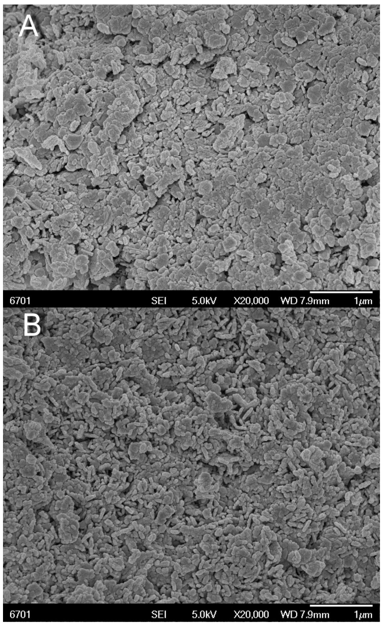

Fig. 3 SEM images of (A) $HTZn_{1.1}Mg_{2.0}Al$ and (B) $Zn_{1.1}Mg_{2.0}AlO_{4.6}$.

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The surface basic properties of these composite oxide catalysts were studied by CO_2-TPD (Fig. 4) and the basic species was assigned according to the temperature at which peaks appeared (Table 1). Obviously, the weak strength basic sites peak of CO_2 desorption appeared at about 75 °C was observed over all the catalysts. For the $Mg_{3.0}AlO_{4.5}$, the desorbed CO_2 peak at 120 °C was attributed to the metal–oxygen pairs (such as Mg-O, Zn-O and Al-O). The peak of CO_2 desorption at 120 °C ascribed to medium strength basic sites was disappeared in $Zn_{3.2}AlO_{4.7}$ catalyst. The CO_2-TPD profile of the reused catalyst $Zn_{1.1}Mg_{2.0}AlO_{4.6}$-reused has more weak strength basic sites and the medium strength basic sites declined. Moreover, it should be mentioned that among all the catalysts, $Mg_{3.0}AlO_{4.5}$ showed the highest desorption temperature of the strong basic sites at about 400 °C, which was attributed to unsaturated oxygen atoms.

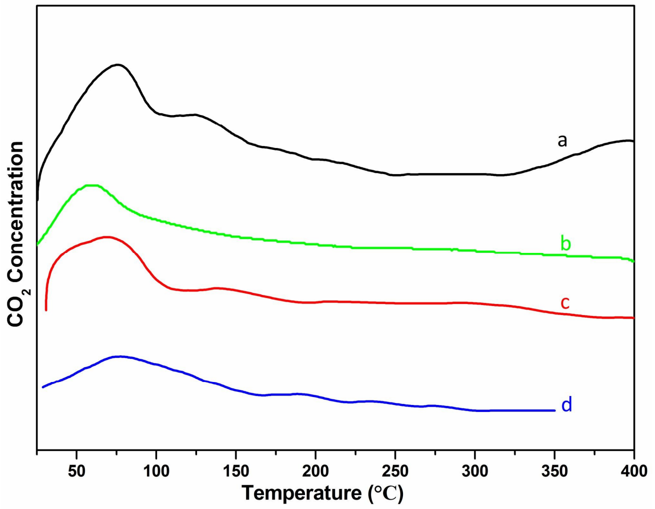
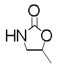
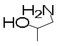
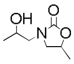


Fig. 4 The CO_2-TPD profiles of (a) $Mg_{3.0}AlO_{4.5}$ (b) $Zn_{3.2}AlO_{4.7}$ (c) $Mg_{1.1}Zn_{2.0}AlO_{4.6}$ (d) $Zn_{1.1}Mg_{2.0}AlO_{4.6}$-reused

3.2 2-oxazolidinones synthesis from urea and epoxides

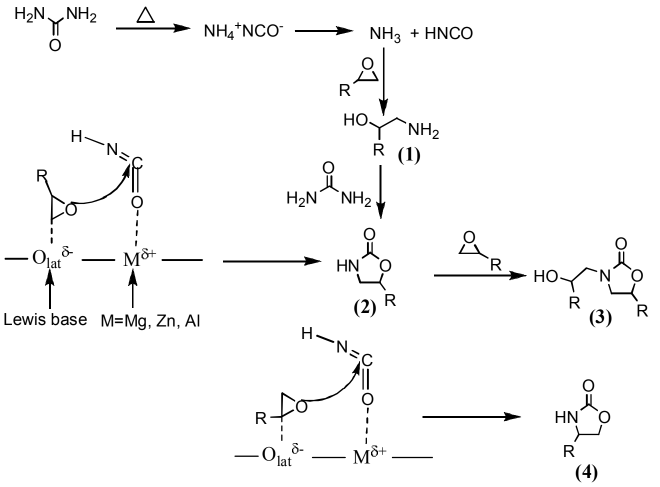
In our initial study, the reaction of urea and propylene oxide (PO) was chosen as the model reaction to explore the catalyst system, Table 2. Generally, the reaction was carried out at 140 °C for 4 h in the presence of different catalysts. In the blank test (entry 1), the yield of 5-methyl-2-oxazolidinone was only 35%, which indicated that catalyst was essential for such reaction proceeded successfully. Yields of 5-methyl-2-oxazolidinone were raised to 50%, 57% and 70% with ZnO, Al_2O_3 and MgO catalyst, respectively (entries 2-4). On the basis of the result of GC–MS, it can be found that the main by-products with these catalysts are 1-amino-2-propanol and hydroxyl functionalized 2-oxazolidinone. As shown in Scheme 2, the 1-amino-2-propanol was formed by the side reaction between NH_3 and PO, which could also be reacted with urea to 5-methyl-2-oxazolidinone. When the 5-methyl-2-oxazolidinone concentration in the reaction mixture was relatively higher, further ring opening of epoxide with the formed 5-methyl-2-oxazolidinone would be occurred and generate the hydroxyl functionalized 2-oxazolidinone. Moreover, trace amount of 4-methyl-2-oxazolidinone was also detected due to the nucleophilic ring opening of the PO at methyl substitute site. When the composite oxides derived from thermal decomposition of hydrotalcites were used as the catalysts (entries 5-7), the ternary composite oxide $Zn_{1.1}Mg_{2.0}AlO_{4.6}$ displayed the highest catalytic activity and 82% yield of 5-methyl-2-oxazolidinone was obtained. The previous reports[38] illustrated that the nucleophilic ring opening of the PO at the less substitute site under basic conditions, followed by intramolecular cyclization to produce the corresponding 5-methyl-2-oxazolidinone. So, it can be conjectured that the yields of 5-methyl-2-oxazolidinone were mainly affected by the strength of the basic sites. Previously, the present authors measured the basic properties of the present oxide catalysts by temperature programmed desorption (TPD) of adsorbed CO_2 (Table 1). It was shown that $Zn_{3.2}AlO_{4.7}$ only has weakly basic sites, while the $Mg_{3.0}AlO_{4.5}$ has strongly basic sites. The lower activity of the $Zn_{3.2}AlO_{4.7}$ might be due to its weak basicity, which was unfavorable for the nucleophilic ring opening of the PO. The catalyst $Mg_{3.0}AlO_{4.5}$ with large amounts of medium basic sites shown relatively lower catalytic activity was considered to be related to the presence of strong basic sites, which would promote the by-product formation. Therefore, incorporation of a zinc component into Mg–Al oxides remarkably affected the basicity strength and the amount of basic sites. Based on the preliminary results, it was concluded that the high activity and selectivity of $Zn_{1.1}Mg_{2.0}AlO_{4.6}$ for 5-methyl-2-oxazolidinone synthesis result from its basic properties. However, the catalyst morphology has little effect on the catalytic performance for such a catalytic system.

Table 2 Synthesis of 5-methyl-2-oxazolidinone from PO and urea with different catalysts and reaction conditions [a]

Entry	Catalyst	T (°C)	t (h)	Yield (%)[b]		
						
1	--	140	4	35	3	15
2	ZnO	140	4	50	14	16
3	Al_2O_3	140	4	57	9	11
4	MgO	140	4	70	3	10
5	$Zn_{3.2}AlO_{4.7}$	140	4	65	6	10
6	$Mg_{3.0}AlO_{4.5}$	140	4	75	7	11
7	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	140	4	82	2	5
8	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	120	4	7	2	1
9	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	130	4	56	5	16
10	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	150	4	45	14	41
11	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	140	2	65	15	2
12	$Zn_{1.1}Mg_{2.0}AlO_{4.6}$	140	8	82	1	6
13	$Zn_{1.1}Mg_{2.0}AlO_{4.6}^{1st}$	140	4	81	3	5
14	$Zn_{1.1}Mg_{2.0}AlO_{4.6}^{2nd}$	140	4	81	3	6
15	$Zn_{1.1}Mg_{2.0}AlO_{4.6}^{3rd}$	140	4	80	4	6

[a] Reaction conditions: 10 mmol PO; 20 mmol urea; 0.05 g catalysts; 120-150 °C; 2-8 h.

[b] Determined by gas chromatography.



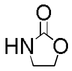
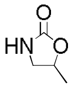
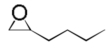
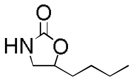
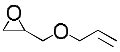
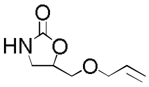
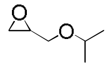
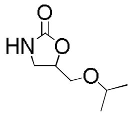
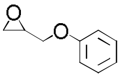
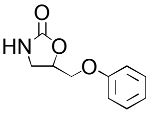
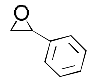
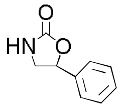
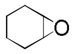
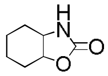
Scheme 2 Possible reaction pathways for the reaction of urea and PO.

Subsequently, the impact of the reaction temperature on the reaction of urea and PO was investigated (entries 8-10). The 5-methyl-2-oxazolidinone yield sharply increases in the temperature range of 120–140 °C and decreases slightly when the reaction temperature exceeds 140 °C, probably due to higher temperature promoted the side reaction reactions (between PO and NH_3 or 5-methyl-2-oxazolidinone), which lead to the selectivity of 1-amino-2-propanol and hydroxyl functionalized 2-oxazolidinone increased. So, 140 °C should be the proper reaction temperature for obtaining higher yield of 5-methyl-2-oxazolidinone. Finally, the impact of reaction time on 5-methyl-2-oxazolidinone synthesis was investigated (entries 11-12). It can be seen that after 4 h reaction the yield of 5-methyl-2-oxazolidinone can reach 82%. Further prolonging the reaction time has no remarkable effect on increasing the yield of 5-methyl-2-oxazolidinone. Apart from the catalytic activity, the reusability of catalyst is another important issue. The results obtained (entries 13-15) indicated that the yield of 5-methyl-2-oxazolidinone slightly decreased to 80% after 3 cycles. This may due to the catalyst leaching (about 36%wt Mg, 11%wt Zn and <0.1%wt Al were leached after 3 recycles), the decline of medium strength basic sites (Table 1) and phase transformations of ZnO during the reaction (a new phase of $Zn(NH_3)_2(NCO)_2$ was observed over spent catalysts in XRD patterns, Fig. 2e).

3.3 Scope of the catalysts

To investigate the limitation and scope of this protocol, the reaction between several different epoxides with urea for corresponding 2-oxazolidinones was further tested using the optimized conditions, and the results are given in Table 3. >90% conversion of epoxides and >80% selectivity of the corresponding 2-oxazolidinones were obtained with terminal epoxides (entries 1–6). The reaction of styrene oxide and urea under 140 °C produces merely 55% selectivity of 5-substituted-2-oxazolidinones, and a very large quantity of 4-substituted-2-oxazolidinones (45%) was also formed. The low selectivity of the 5-substituted-2-oxazolidinones for the styrene oxide (entry 7) might be attributed to the conjugative effect derived from the aromatic ring, which would beneficial attack at the carbon atom at which phenyl substitute was connected to afford 4-substituted-2-oxazolidinones.[39] When the cyclohexene oxide (entry 8) was used for the synthesis of 2-oxazolidinones, 80% conversion of disubstituted epoxide and 64% selectivity the corresponding 2-oxazolidinones were obtained, the lower activity towards the synthesis of 2-oxazolidinones compared with other epoxides might be due to the high hindrance of cyclohexene oxide. From the preliminary results, it can be conjectured that the basic $Zn_{0.8}Mg_{1.9}AlO_{4.2}$ catalyst has good catalytic performance for various 5-substituted-2-oxazolidinones synthesis by the epoxide opening reaction with urea.

Table 3 Synthesis of 2-oxazolidinones from various epoxides and urea [a]

Entry	Epoxide	Major product	Conv. (%)	Sel. (%)[b]
1			99	89
2			99	81
3			99	88
4			92	80
5			94	87
6			96	88
7			99	55
8			80	64

[a] Reaction conditions: 10 mmol epoxides; 20 mmol urea; 0.05 g $Zn_{1.1}Mg_{2.0}AlO_{4.6}$; 140 °C; 8 h. Conversion and selectivity were determined by gas chromatography.

[b] Selectivity of the 5-substituted-2-oxazolidinone.

4. Conclusions

Production of value-added chemicals using urea as an active form of carbon dioxide is favorable to the sustainable development of the chemical industry. In this work, various 2-oxazolidinones were successfully synthesized from urea and epoxides in the absence of any solvent. This efficient and green protocol has the advantages of environmental friendliness, high yields and operational simplicity.

Acknowledgments

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Notes and references

1 M. Mikkelsen, M. Jørgensen, F. C. Krebs, *Energy Environ. Sci.,* 2010, **3**, 43-81.
2 J. Hu, J. Ma, Q. Zhu, Z. Zhang, C. Wu, B. Han, *Angew. Chem., Int. Ed.*, 2015, **54**, 5399-5403.
3 R. Ma, L. He, Y. Zhou, *Green Chem.*, 2016, **18**, 226-231.
4 Z. Yang, L. He, Y. Zhao, B. Li, B. Yu, *Energy Environ. Sci.*, 2011, **4**, 3971-3975.
5 A. Behr, *Angew. Chem., Int. Ed.*, 1988, **27**, 661-678.
6 M. Shi, K. M. Nicholas, *J. Am. Chem. Soc.*, 1997, **119**, 5057-5058.
7 F. Shi, Y. Deng, T. SiMa, J. Peng, Y. Gu, B. Qiao, *Angew. Chem., Int. Ed*. 2003, **42**, 3257-3260.
8 C. Tai, M. Huck, E. McKoon, T. Woo, P. Jessop, *J. Org. Chem.* 2002, **67**, 9070-9072.
9 R. Nomura, Y. Hasegawa, M. Ishimoto, T. Toyosaki, H. Matsuda, *J. Org. Chem*. 1992, **57**, 7339-7342.
10 G. Verardo, P. Geatti, P. Strazzolini, *Synth. Commun.* 2007, **37**, 1833-1844.
11 P. Wang, Y. Ma, S. Liu, F. Zhou, B. Yang, Y. Deng, *Green Chem.*, 2015, **17**, 3964-3971.
12 Q. Li, N. Zhao, W. Wei, Y. Sun, *Catal. Today*, 2006, **115**, 111-116.
13 P. Wang, S. Liu, F. Zhou, B. Yang, A. S. Alshammari, L. Lu, Y. Deng, *Fuel Process. Technol.*, 2014, **126**, 359-365.
14 P. Wang, S. Liu, F. Zhou, B. Yang, A. S. Alshammari, Y. Deng, *RSC Adv.*, 2015, **5**, 19534-19540.
15 M. Ito, *JP. Pat.*, 1996, 0892167.
16 M. Ito, *JP. Pat.*, 1997, 9104658.
17 M. Mullner, G. Stern, M. Rossler, *US. Pat.*, 1991, 5043444.
18 T. Ikariya, M. Itagaki, M. Mizuguchi, *EP. Pat.*, 1991, 0437258.
19 A. Kumar, S. Koul, T. K. Razdan, K. K. Kapoor, *Tetrahedron Lett.*, 2006, **47**, 837-842.
20 M. G. Barthakur, M. Borthakur, P. Devi, C. J. Saikia, A. Saikia, U. Bora, A. Chetia, R. C. Boruah, *Synlett*, 2007, **2**, 223-226.
21 A. Kumar, R. A. Maurya, *Tetrahedron Lett.*, 2007, **48**, 4569-4571.
22 M. Dabiri, A. S. Delbari, A. Bazgir, *Synlett*, 2007, **5**, 821-823.
23 L. D. S. Yadav, A. Rai, V. K. Rai, C. Awasthi, *Synlett*, 2007, **12**, 1905-1908.
24 G. A. Artamkina, A. G. Sergeev, M. M. Stern, I. P. Beletskaya, *Synlett*, 2006, **2**, 235-238.
25 Md. M. Baag, N. P. Argade, *Synthesis*, 2006, 1005-1008.
26 R. A. W. Neves Filho, R. M. Srivastava, *Molecules*, 2006, **11**, 318-324.
27 G. Zappia, E. Gacs-Baitz, G. Delle Monache, D. Misiti, L. Nevola and B. Botta, *Curr. Org. Chem.,* 2007, **4**, 81-135.
28 X. Dou, L. He and Z. Yang, *Synth. Commun.,* 2012, **42**, 62-74.
29 T. A. Mukhtar and G. D. Wright, *Chem. Rev.*, 2005, **105**, 529-542.
30 A. W. Miller and S. T. Nguyen, *Org. Lett.*, 2004, **6**, 2301-2304.
31 X. Lin, Z. Yang, L. He, Z. Yuan, *Green Chem.*, 2015, **17**, 795-798.
32 Y. Wu, L. He, Y. Du, J. Wang, C. Miao, W. Li, *Tetrahedron*, 2009, **65**, 6204-6210.
33 R. A. Watile, D. B. Bagal, K. M. Deshmukh, K. P. Dhake, B. M. Bhanage, *J. Mol. Catal. A: Chem.*, 2011, **351**, 196-203.
34 S. I. Fujita, H. Kanamaru, H. Senboku, M. Arai, *Int. J. Mol. Sci.*, 2006, **7**, 438-450.
35 K. I. Tominaga, Y. Sasaki, *Synlett*, 2002, **2**, 307-309.
36 R. Ju ´arez, P. Concepci ´on, A. Corma, H. Garc´ı a, *Chem. Commun.*, 2010, **46**, 4181-4183.
37 M. J. Climent, A. Corma, P. D. Frutos, S. Iborra, M. Noy, A. Velty, P. Concepci ´on, *J. Catal.*, 2010, **269**, 140-149.
38 S. Bonollo, F. Fringuelli, F. Pizzo and L. Vaccaro, *Synlett*, 2007, **17**, 2683–2686.
39 S. Bonollo, D. Lanari and L. Vaccaro, *Eur. J. Org. Chem.*, 2011, **14**, 2587–2598.

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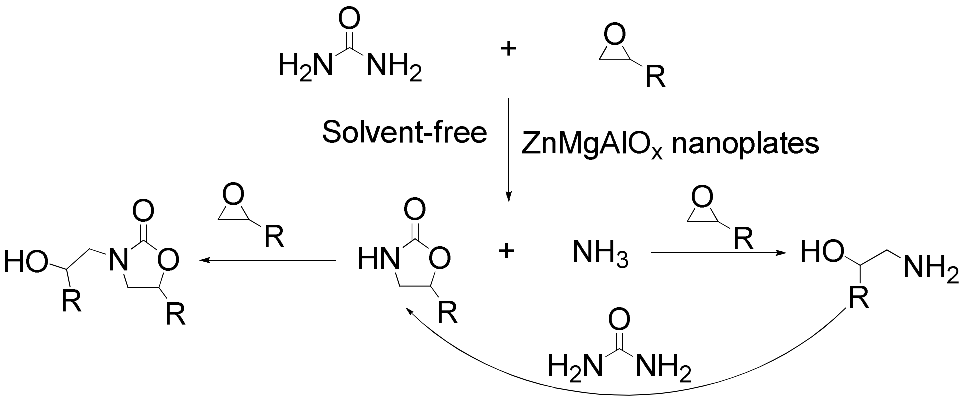

Solvent-free synthesis of 2-oxazolidinones from urea and epoxides over Zn-modified mesoporous Mg–Al nano-oxides.