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# Lewis Pairs for Ring-Opening Alternating Copolymerization of Cyclic Anhydrides and Epoxides

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## Abstract

Simple and highly active catalytic process for ring-opening alternating copolymerization (ROAC) of cyclic anhydrides and epoxides still remains a key challenge. Herein, we described an effective group of versatile and low-toxic zinc dicarbyl/amine Lewis pairs for the ROAC in this work. The facile route showed high catalytic activity ( $\text{TOF} \leq 210 \text{ h}^{-1}$  at  $110^\circ\text{C}$ ) and perfectly alternating selectivity ( $> 99\%$ ). An unexpected highly regioselective ring-opening of asymmetric epoxides (PO, ECH and SO) was also achieved by the combination of zinc alkyls (or aryls) and amines. Of unique, deprotonation side reaction of  $\alpha\text{-H}$  of anhydrides with organic bases was uncovered, and subsequently was inhibited by using nonpolar solvents and Lewis acid/base pairs. Thus, an array of polyesters was synthesized by the coupling of various anhydrides (PA, CHA, SA and NA) and epoxides (CHO, PO, ECH and SO) under the same Lewis pairs. Further variable temperature  $^1\text{H}$  NMR spectra and MALDI TOF MS analysis were performed to understand possible mechanism and microstructure. The experimental results indicated that zwitterionic alkoxides and carboxylates intermediate alternately formed to enhance ester repeat units in chain initiation and propagation. This work provides a simple and green catalytic strategy to prepare diversified polyesters from the ROAC process of cyclic anhydrides and epoxides with considerable catalytic activity and alternating selectivity.

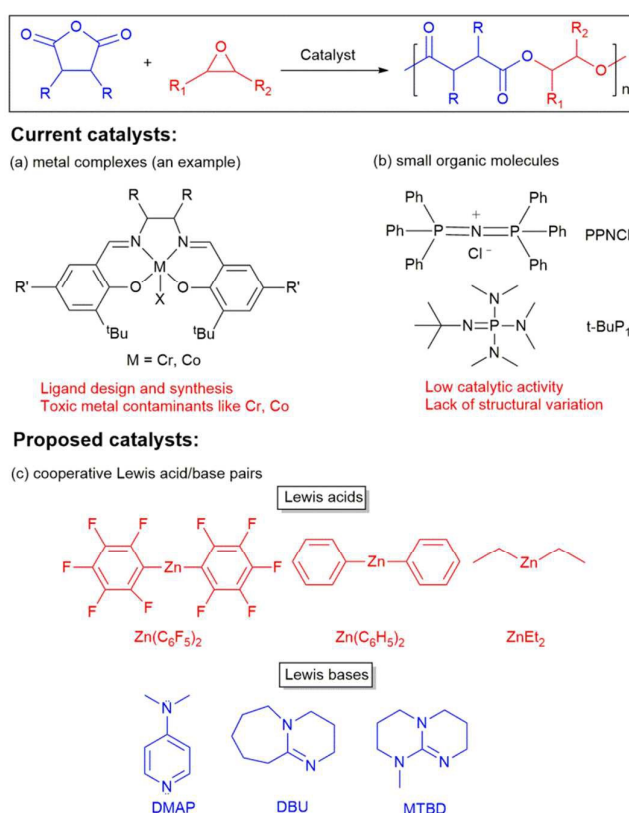
## Introduction

The development of simple and green catalytic process is a growing demand for the preparation of various polymers.<sup>1</sup> The versatility, commercial accessibility and high activity of several catalysts has led to them being widely applied in preference of more traditional metal/ligand combinations, such as organic bases,<sup>2</sup> hydrogen-bonding organocatalysts<sup>1d,3</sup> and Lewis pairs.<sup>4-7</sup> Indeed, the advancement of catalytic systems has been represented by ring-opening polymerization (ROP) of cyclic esters.<sup>2-6</sup> Importantly, Lewis pairs, the combination of electron-pair-donors and electron-pair-acceptors, have been employed in the ROP of lactide or lactones, including  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{PMP}$ ,<sup>5a</sup>  $\text{MgCl}_2/\text{NHC}$ ,<sup>5b</sup>  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}$ ,<sup>6</sup>  $\text{MgCl}_2/\text{NHO}$ <sup>5c</sup> and  $\text{Al}(\text{C}_6\text{F}_5)_3/\text{NHO}$ .<sup>5d</sup> In all cases, the presence of both a Lewis acid (LA) and a Lewis base (LB) has been essential in order to enhance polymerization activity and product selectivity. With the powerful strategy, well-defined polyesters and diblock copolyesters could be synthesized with the elimination of transesterification side reactions. However, as an alternative route to polyesters, ring-opening alternating copolymerization (ROAC) of cyclic anhydrides and epoxides catalyzed by aforementioned Lewis pairs still remains in its vacant development.

In contrast to step-growth polycondensation of diacids or diesters with diols, ROAC of cyclic anhydrides and epoxides is an atom-economic and controlled approach to polyesters with the advantage of low energy input.<sup>8</sup> Meanwhile, the ROAC process also has another advantage to architect miscellaneous polyesters over ROP of cyclic ester monomers, in which the structures and properties of polyesters can be easily modulated by changing anhydrides or epoxides (Scheme 1).<sup>8</sup> Furthermore, many anhydrides and epoxides reported for the ROAC could derive from renewable resources, like phthalic anhydride (PA),<sup>9</sup> cyclohexanedicarboxylic anhydride (CHA), maleic anhydride (MA)<sup>10</sup> and succinic anhydride (SA)<sup>11</sup>, as well as cyclohexene oxide (CHO)<sup>9c</sup> and epichlorohydrin (ECH).<sup>12</sup> The corresponding polyesters are interesting examples sourced from sustainable feedstocks.

A wide range of metal complexes has been used to catalyze the ROAC of anhydrides and epoxides. In 2007, Coates *et al.* have ever made a big breakthrough by using  $\beta$ -diiminate zinc complex with withdrawing substituent on the ligand, yielding aliphatic polyesters with relatively high reactivity ( $\text{TOF} = 31 \text{ h}^{-1}$  at  $50^\circ\text{C}$ ).<sup>11b</sup> Since the seminal work, a diverse array of metal-based

complexes was developed, including chromium,<sup>9c,11a,d-f,12b,c,13</sup> cobalt,<sup>9c,11a,c,e,f,12b,d,13a,h</sup> manganese,<sup>11a,e,f,14</sup> aluminum,<sup>11a,e,f,12b,13a,h,15</sup> zinc,<sup>16</sup> magnesium<sup>16</sup> and iron.<sup>15b,17</sup> In general, the chromium and cobalt-based salen catalysts (Scheme 1a) exhibited higher TOF values and outstanding regioselectivity.<sup>9c,11a,e,f,12b,d,13a</sup> Except for  $\beta$ -diiminate zinc, other zinc/ligand complexes have also been explored to catalyze the ROAC of anhydride/epoxide, showing excellent chemoselectivity and moderate catalytic activity.<sup>16</sup> Subsequently, to achieve satisfying catalytic activity, chemo- and regioselectivity, optimization of catalysts focused previously on the design of metal centers and their ligand frameworks.



**Scheme 1.** The ROAC of cyclic anhydrides and epoxides to synthesize polyesters using various catalysts: (a) metal complexes reported in previous work; (b) small organic molecules reported and (c) Lewis pairs used in the present work.

Unfortunately, to the best of our knowledge, only a few studies laid emphasis on simple and green catalysts (Scheme 1b) for the ROAC approach in the literature.<sup>18</sup> In 2015, Theato and Liu<sup>18a</sup> reported that bis(triphenylphosphine)iminium chloride (PPNCl) could mediate the ROAC of norbornene anhydride (NA) and CHO with an optimized TOF of 32 h<sup>-1</sup> at 110 °C. In 2017, Merna

and co-workers<sup>18b</sup> found that PPNCI promoted the ROAC of CHO and PA with a TOF of 23 h<sup>-1</sup> at 110 °C. Recently, Zhao and coworkers revealed that the ROAC of PA and ethylene oxide (EO) was efficiently initiated by 1,4-benzenedimethanol (BDM) and catalyzed by phosphazene superbases (*t*-BuP<sub>1</sub>).<sup>18c</sup> The new system highlighted a living nature with controlled molecular weights and very narrow distributions (PDI < 1.1) by self-buffering mechanism; but somewhat low reactivity was observed at 60 °C in tetrahydrofuran solvent. Obviously, there are still lower catalytic activity and lack of structural variation of small organic molecules compared to metal/ligand complexes. Also, we have not still found that single organocatalyst could control regioselectivity of asymmetric epoxides (such as propylene oxide) for the ROAC of anhydrides/epoxides in the literature. Therefore, the development of highly active and simple catalysts for selective ROAC of anhydrides and epoxides continues to be an inspiring objective.

Here, we anticipated that the combination of simple and proper Lewis acids with common organic bases (Scheme 1c) could realize the ROAC of anhydrides with epoxides. For one, to avoid the labor-consuming synthesis of ligands and undesirable toxic metal contaminants like chromium and cobalt, more environment-friendly ZnR<sub>2</sub> and organic bases were directly used to promote the copolymerization.<sup>19a-c</sup> In the proceeding, N-heterocyclic organobases showed relatively low cytotoxicity at a low concentration.<sup>19d</sup> Removal of such organobase residues was also more convenient than metal/ligand combinations.<sup>19e</sup> For another, in contrast to small organic molecules reported, cooperative Lewis pairs provided an attractive potential that the catalytic properties could usually be finely tuned to compromise selectivity and reactivity. Besides, the new catalytic pairs were developed based on the hypothesis that Lewis acid might activate epoxides for ring-opening and Lewis base might act as nucleophile to initiate polymerization. The independent variability of both components maybe allowed for a simultaneous increase of polymerization rates and selectivity by simple means.

## Results and Discussion

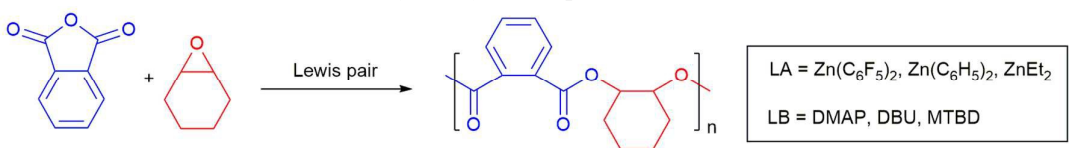
**ROAC of PA and CHO.** The ROAC of PA and CHO was firstly selected as the model reaction with the molar ratio of 1:1:100:500 of LA, LB, PA and CHO in bulk. At 110 °C, Zn(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>/DMAP (1:1) pair could efficiently catalyze the copolymerization with a moderate catalytic activity (run 1, Table 1). A complete PA conversion was achieved within 1.5 h, yielding perfectly alternating

copolymer with ester linkage > 99%. No polyether segment was observed even in excess CHO (see Figures S1-S3 in Supplementary Information). Furthermore, homopolymerization of excess epoxides did not occur even though the reaction time was extended to 9 h (Figure S4). While it was noteworthy that  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{PPh}_3$ ,  $\text{B}(\text{C}_6\text{F}_5)_3/\text{DMP}$ ,  $\text{B}(\text{C}_6\text{F}_5)_3/\text{PPh}_3$  and  $\text{Al}^t\text{Bu}_3/\text{DMP}$  Lewis pairs were inefficient in the ROAC (runs 1-4, Table S1). A mass of ether linkages in the polymers showed the inferior selectivity of these Lewis pairs, suggesting that steric effect and matched acidity-basicity of Lewis pairs were the decisive factors to produce alternating copolymers, which agreed well with ring-opening copolymerization of COS/epoxides.<sup>7</sup> With the efficient  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMP}$  Lewis pair, PA monomer was consumed faster when changing  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMP}$  molar ratio into 1:2 (run 2, Table 1), whereas  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMP}$  in 2:1 ratio generated poly(ester-co-ether) with 73% ether linkage (run 3, Table 1). The results indicated that the molar ratio of LA/LB greatly affects the chemoselectivity. To extend the scope of the Lewis pairs used in the ROAC, some other organometallic zinc dicarbonyl species and amines were further evaluated. Obviously, the combination of DMP with  $\text{Zn}(\text{C}_6\text{H}_5)_2$  or  $\text{ZnEt}_2$  can also mediate the copolymerization without sacrificing any catalytic activity or structural selectivity (runs 4&5, Table 1). However, replacing DMP with DBU or MTBD led to a depressed catalytic efficiency and yet perfect alternating degree under the same conditions (runs 6&7, Table 1). The results indicated that the nature of Lewis bases had a stronger influence on the copolymerization rate than Lewis acids under the new catalyst system. In addition, the copolymerization rate of PA and CHO depended remarkably on solvent effect. As expected, PA conversion was lower in xylene compared to bulk condition (run 8, Table 1). Dilution factors of CHO could account for this phenomenon, which has been demonstrated to be common for many metal/ligand complexes.<sup>11d,16a</sup> While the copolymerization rate was much lower in a more polar solvent like 1,2-dichlorobenzene (oDCB) (run 9, Table 1), indicating that solvent polarity considerably affected Lewis pairs-mediated the ROAC of PA/CHO. We speculated a more polar medium would dissociate the interacting Lewis pairs,<sup>1e</sup> favoring a slower propagation rate as compared to the experiment carried out in xylene.

Further kinetic experiments were performed to test chain initiation and the dependence of copolymerization rates versus comonomers by pipetting aliquots during the copolymerization (Figures S11&S12). In neat epoxide, the kinetic plots exhibited no induction period and a good linearity about PA conversion, suggesting the ROAC expressly followed zero-order kinetics with

respect to PA concentration for all of the Lewis pairs employed. Recently, Coates *et al.* also deserved the same zero order dependence of the rate on norbornene-2,3-dicarboxylic anhydride (NA) by using (salph)AlCl/PPNCl.<sup>15c</sup> This similar example indicated the ring-opening of anhydrides was in a fast process. Obviously, LBs rather than LAs played a dominant role in the catalytic activity according to the slope of kinetic plots.

**Table 1.** The ROAC of PA and CHO catalyzed by Lewis pairs.<sup>a</sup>



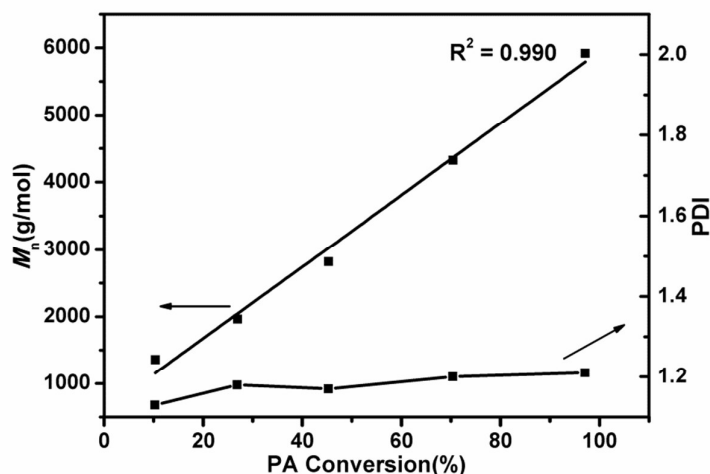
Run	Lewis pair	LA/LB/PA/CHO	t (h)	Conv. (%) <sup>b</sup>	TOF (h <sup>-1</sup> ) <sup>c</sup>	Alternating (%) <sup>d</sup>	degree	<i>M<sub>n</sub></i> , calc. (kDa) <sup>e</sup>	<i>M<sub>n</sub></i> , GPC (kDa) <sup>e</sup>	PDI <sup>e</sup>
1	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:1:100:500	1	69	69	>99		17.0	6.1	1.21
2	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:100:500	0.8	93	116	>99		11.4	5.6	1.20
3	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	2:1:100:500	2.5	30	12	27		15.3	16.8	1.93
4	Zn(C <sub>6</sub> H <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:100:500	0.8	96	120	>99		11.8	6.9	1.17
5	ZnEt <sub>2</sub> /DMAP	1:2:100:500	0.75	95	127	>99		11.7	7.1	1.22
6	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DBU	1:1:100:500	1.5	77	51	>99		18.9	5.9	1.23
7	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /MTBD	1:1:100:500	1.5	48	32	>99		11.8	4.7	1.11
8 <sup>f</sup>	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:100:100	3	99	33	>99		12.2	7.7	1.18
9 <sup>g</sup>	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:100:100	3	84	28	>99		10.3	3.0	1.12
10	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:200:500	1.5	96	128	>99		23.6	13.5	1.22
11	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:400:500	3	86	115	>99		42.3	17.9	1.13
12 <sup>h</sup>	Zn(C <sub>6</sub> F <sub>5</sub> ) <sub>2</sub> /DMAP	1:2:100:500	9	>99	-	>99		12.3	10.5	1.27

<sup>a</sup> Unless otherwise mentioned, the copolymerizations were carried out at 110 °C in neat epoxide with PA concentration of 2 mol/L. <sup>b</sup> PA conversion was determined by <sup>1</sup>H NMR. <sup>c</sup> TOF = turnover frequency. <sup>d</sup> Ether linkage was determined *via* <sup>1</sup>H NMR by integrating ester and ether signals. <sup>e</sup> *M<sub>n</sub>* and PDI were determined by GPC analysis. <sup>f</sup> In xylene. <sup>g</sup> In oDCB. <sup>h</sup> PA was sublimed three times.

Under aforementioned conditions, moderate MWs and narrow molecular weight distributions in the comonomer molar ratio of 100:500 was observed in the resulting poly(PA-*alt*-CHO). Evolution of the number average molecular weights (*M<sub>n</sub>*) against PA conversion for the ROAC was in a linear correlation with a narrow molecular weight distribution (PDI ~ 1.20) (Figure 1), suggesting a controlled behavior of the copolymerization system. Gel permeation chromatography (GPC) analysis revealed that data of molecular weights (MWs) obtained from crude reaction mixture was in a good accordance with these obtained from precipitated polymers (Figure S14-S16).



The resultant alternating copolymers remained unimodal GPC traces at low PA conversion (Figure S14). Nevertheless with PA conversion increasing, the samples obtained from a single polymerization reaction showed bimodal GPC traces (Figure S15&S16). Besides, the polyesters had lower MWs than calculated ones. With molar ratio of monomers increased to 200:500 and 400:500 (runs 10&11, Table 1), molecular weights of corresponding polymers rose to 13.5 and 17.9 kg/mol, respectively. Actually, lower MWs and bimodal GPC traces implied the presence of adventitious water or trace amounts of hydrolysed anhydride, which acted as a bifunctional chain transfer agent. The bifunctional agent would be expected to propagate at the similar rate as chains initiated from catalysts, leading to chain growth from both hydroxyl moieties (see Figure S43 and Scheme S1) and two distinct distributions of MWs differing by approximately a factor of 2.<sup>9c,11d-f, 13a,f,g,16a,18a,b</sup> Considering the presence of hydrolysed anhydride, PA was refined three times by sublimation. The refined PA led to an appreciable increase of MWs (run 12, Table 1), suggesting that hydrolysed PA acted as an efficient initiator of the copolymerization. When the copolymerization reaction was further extended to 9 h, molecular weight distribution widen from 1.16 to 1.27 (Figure S17). The result showed that intermolecular transesterification side reaction tended to happen after full conversion of PA was reached (intermolecular transesterification was not observed, *vide infra*).

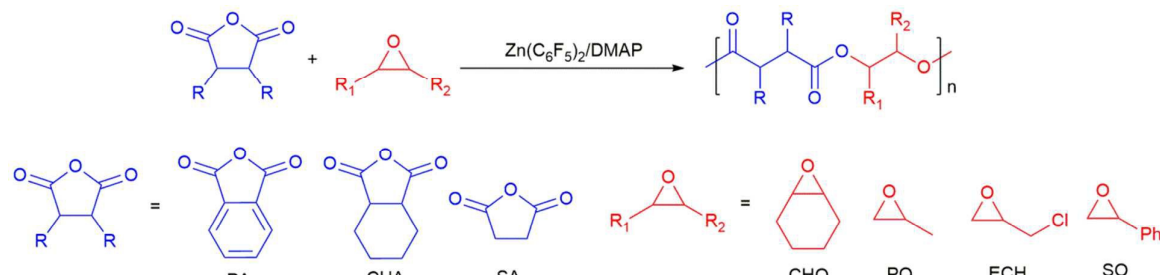


**Figure 1.** Plots of  $M_n$  and PDI versus PA conversion.

**ROAC of different anhydrides and epoxides.** After model experiments investigation of PA/CHO, various comonomers were selected to explore the feasibility for the synthesis of structurally diverse polyesters. The results suggested that  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}$  pair could effectively

catalyze the ROAC of PA with a variety of epoxides for the synthesis of various semiaromatic polyesters with well-defined structures (runs 1-5, Table 2). The type of epoxides dramatically affected copolymerization rates. Propylene oxide (PO), one of the widest studies, had a similar reactivity with CHO in this work (run 1, Table 2). While ECH exhibited an enhanced polymerization rate (TOF = 210 h<sup>-1</sup>) to afford polyesters (run 2, Table 2). High reactivity of ECH could attribute to electron-withdrawing chlorine atom.<sup>12d</sup> However, a lower molecular weight was observed from poly(PA-*alt*-ECH), in which chain transfer might be faster due to the stronger polar ECH. Decreasing temperature from 110 °C to 60 °C resulted in a slower polymerization rate (run 4, Table 2), but the TOF value was still eight times as high as the system of alcohol/phosphazene base.<sup>18c</sup> Another electron-poor styrene oxide (SO) was also viable comonomers with a higher TOF value than CHO and PO (run 5, Table 2).

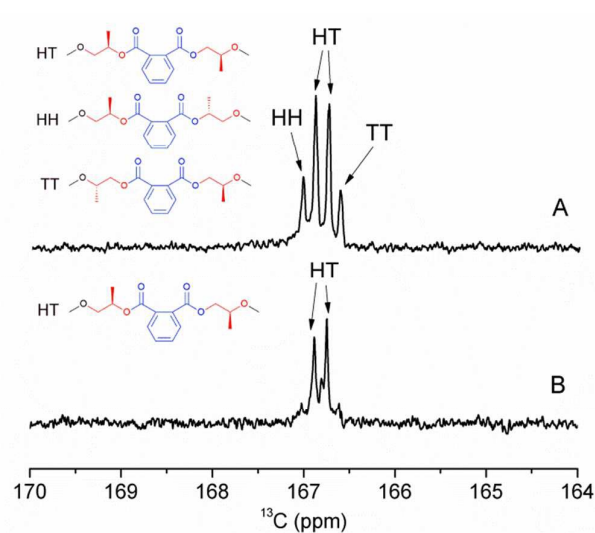
**Table 2.** The ROAC of various anhydrides and epoxides catalyzed by Zn(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>/DMAP pair.<sup>a</sup>



Run	Anhydride	Epoxide	Solvent	t (h)	Conv. (%) <sup>b</sup>	TOF (h <sup>-1</sup> ) <sup>c</sup>	Alternating degree (%) <sup>b</sup>	M <sub>n</sub> (kDa) <sup>d</sup>	PDI <sup>d</sup>
1	PA	PO	bulk	0.8	81	101	>99	7.4	1.25
2	PA	ECH	bulk	0.4	84	210	>99	2.1	1.17
3 <sup>e</sup>	PA	CHO	bulk	4	81	20	>99	5.6	1.21
4 <sup>f</sup>	PA	ECH	bulk	2	84	42	>99	2.6	1.23
5	PA	SO	bulk	0.5	83	166	>99	3.8	1.28
6	SA	CHO	bulk	2	21	11	33	1.9	1.03
7	SA	CHO	xylene	1	41	41	>99	5.3	1.05
8	SA	CHO	oDCB	2	14	7	72	– <sup>g</sup>	– <sup>g</sup>
9	CHA	CHO	bulk	4	56	14	75	5.4	1.07
10	CHA	CHO	xylene	4	82	21	96	9.8	1.09

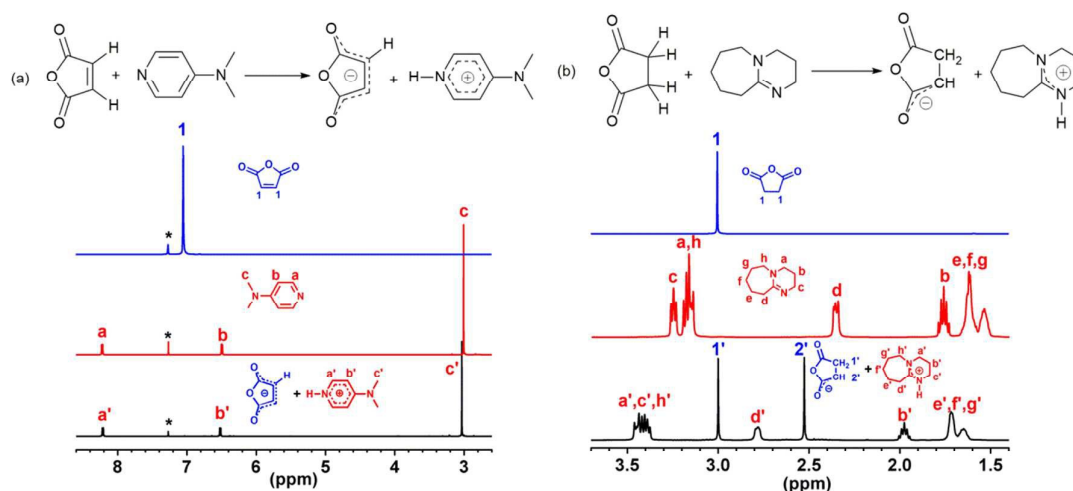
<sup>a</sup> Unless otherwise mentioned, copolymerizations were carried out at 110 °C; Zn(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>/DMAP/Anhydride/Epoxide = 1:2:100:500 in bulk or 1:2:100:100 in solution. <sup>b</sup> The conversion of anhydride was determined by <sup>1</sup>H NMR. <sup>c</sup> TOF = turnover frequency. <sup>d</sup> Determined by GPC analysis. <sup>e</sup> At 80 °C. <sup>f</sup> At 60 °C. <sup>g</sup> Not defined.

In general, ring-opening of asymmetric terminal epoxides (including PO, ECH and SO) could occur either at the methylene or at the more sterically hindered methine, in which the resultant polyesters would contain head-to-tail (HT), head-to-head (HH) and tail-to-tail (TT) junctions. When ring-opening of epoxides occurred exclusively at one of these positions *via* a regioselective catalyst,<sup>12c,d</sup> regioregular polyesters could be fabricated. <sup>13</sup>C NMR spectra of the resultant polyesters showed useful information for the analysis of regio(ir)regular insertion. As shown in Figure 2, 166.87 and 166.73 ppm of carbon chemical shifts were assigned to carbonyl signals from HT linkages for poly(PA-*alt*-PO). Two separate resonance peaks at 167.01 and 166.60 ppm represented carbonyl signals of HH and TT linkages, respectively. Clearly, a highly regioselective ROAC of PA with PO could be achieved by using Zn(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>/DMAP (1:1) pair (Figure 2B). In order to verify quantitatively the regioregularity of copolymers, enantiopure terminal epoxides (*S*-PO and *S*-SO) were used for the ROAC. Subsequently, enantiopurity of diols resulting from the hydrolysis of the resultant polyesters was determined by gas chromatography analysis.<sup>11c,13h</sup> The high enantiomeric ratio, representing the percent HT junctions in the copolymers, certifying the regioselective ROAC of asymmetric terminal epoxides (PO) with anhydrides (Figure S21). Indeed, this was the first observation of regioselective insertion for the ROAC by using simple catalytic system. We speculated the interacting Lewis pair could exclusively attack the less sterically crowded methylene carbon of PO in chain initiation and propagation.



**Figure 2.** <sup>13</sup>C NMR spectra of carbonyl regions of poly(PA-*alt*-PO): (A) regiorandom copolymer and (B) regioregular copolymer catalyzed by Zn(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>/DMAP (1:1).

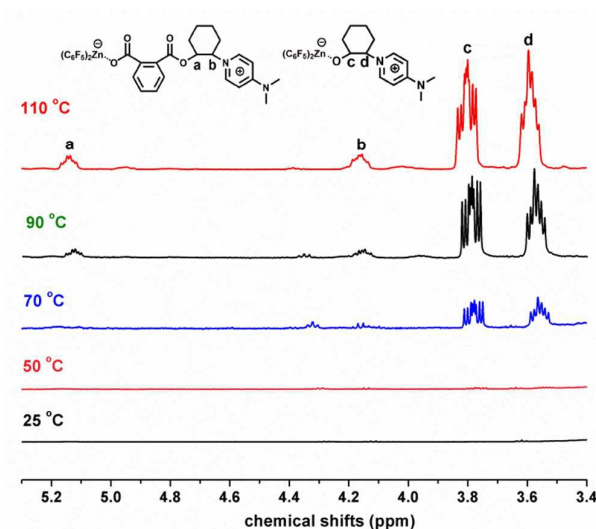
Next, the ROAC of different anhydrides with CHO was also evaluated by using  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}$  pair. For SA/CHO copolymerization, bulk mode revealed a low TOF value and inferior alternating selectivity (run 6, Table 2). However, an unanticipated result suggested that nonpolar xylene was more beneficial to the copolymerization (run 7, Table 2). In contrast, oDCB solvent played a poorer role in the ROAC of SA and CHO (run 8, Table 2). Polar medium offered rather low conversions and a mass of polyether segment compared with those in xylene. Inspired by proton transfer reactions of weak carbon-acids with amine bases in polar solvent,<sup>20</sup> we envisioned that the  $\alpha$ -H of cyclic anhydrides activated by carbonyl is rendered sufficiently activity to undergo deprotonating with organic bases without the need for intervention by other catalysts. That is, the  $\alpha$ -H was easily extracted by the inherent organic amines to yield the undesired salts in stoichiometric amounts in strong polar medium. The propensity of amines to react with common anhydrides bearing  $\alpha$ -H easily results in their inactivation, which shed light on the observation that SA was difficult to copolymerize with epoxides in polar medium by using organic bases.<sup>18b</sup> The deprotonation was revealed by the  $^1\text{H}$  NMR spectra involving different anhydrides (MA and SA) and amines. At 25 °C, the observations that  $\alpha$ -H signals of MA and SA disappeared or decreased with equivalent amines (the  $\alpha$ -H signal was not observed because of fast proton exchange between MA and DMAP), exhibited a high reactivity for deprotonation in polar  $\text{CDCl}_3$  (Figure 3). A contrastive experiment was performed to monitor  $\alpha$ -H signals of MA in nonpolar toluene- $d_8$  (Figure S29). The  $^1\text{H}$  NMR spectra revealed that nonpolar solvents could suppress the deprotonation between  $\alpha$ -H of anhydrides and amines in some degree. Importantly, as shown in Figure S30, the  $^1\text{H}$  NMR spectra of  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}/\text{MA}$  in polar  $\text{CDCl}_3$  also showed the signals at 7.05 ppm assigned to the  $\alpha$ -H of MA. Obviously, the interaction of LAs with LBs impeded the deprotonation side reaction as well. Intrigued by these results, we selected nonpolar solvents to dilute polar epoxides. In this endeavor, the ROAC of anhydrides bearing  $\alpha$ -H and epoxides can be achieved under the facile conditions (Figure S32-S40).



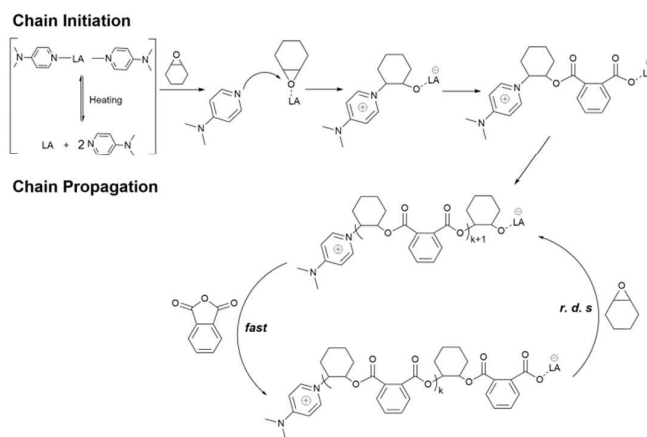
**Figure 3.** Possible structures of the products for the proton transfer of anhydrides bearing  $\alpha$ -H and Lewis bases in polar  $\text{CDCl}_3$ , (a) MA/DMAP, (b) SA/DBU.

**Mechanism and microstructure analysis.** To gain insight into the mechanism of the ROAC catalyzed by Lewis pairs, we performed variable temperature (VT)  $^1\text{H}$  NMR experiments about well reactive PA/CHO substrate. Firstly, as our previous report,  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}$  had a coordination to generate tetrahedron complex at low temperature.<sup>6</sup> With temperature elevating from 25  $^\circ\text{C}$  to 110  $^\circ\text{C}$ , the interaction of the LA and the LB was impaired. Further, no obvious chemical shifts were observed in VT  $^1\text{H}$  NMR spectra of  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{PA}$ , revealing an impossible pathway involving that  $\text{Zn}(\text{C}_6\text{F}_5)_2$  facilitated PA (Figure S41). Meanwhile, considering that sole  $\text{Zn}(\text{C}_6\text{F}_5)_2$  was very good at catalyzing ROP of CHO to form polyether, we clearly concluded that LA acted as epoxide activator with the presence of LBs. During our study, two elegant publications about ring-opening copolymerization of  $\text{CO}_2$ /epoxides and  $\text{COS}$ /epoxides promoted by  $\text{BEt}_3/\text{LB}$  similarly proved the rationality that LA served as epoxide activator for ring-opening.<sup>7,1c</sup> In addition, the VT  $^1\text{H}$  NMR spectra of  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}/\text{CHO}$  in  $\text{C}_2\text{D}_2\text{Cl}_4$  in an NMR tube showed that the protons chemical shifts at 3.60 and 3.79 ppm gradually appeared (Figure S42), strongly suggesting that CHO was firstly activated and ring-opened by Lewis pairs. Then a zwitterion generated with an amine initiator in one end and  $\text{Zn}(\text{C}_6\text{F}_5)_2$  in the other end (Scheme 2). Subsequently, the active alkoxide selectively reacted with an anhydride to form an ester unit and a carboxylate nucleophile (5.14 and 4.17 ppm in Figure 4). In chain propagation cycle,  $\text{Zn}(\text{C}_6\text{F}_5)_2$  worked to activate epoxides. Alkoxide and carboxylate intermediates alternately regenerated, enhancing one ester unit into growing chain

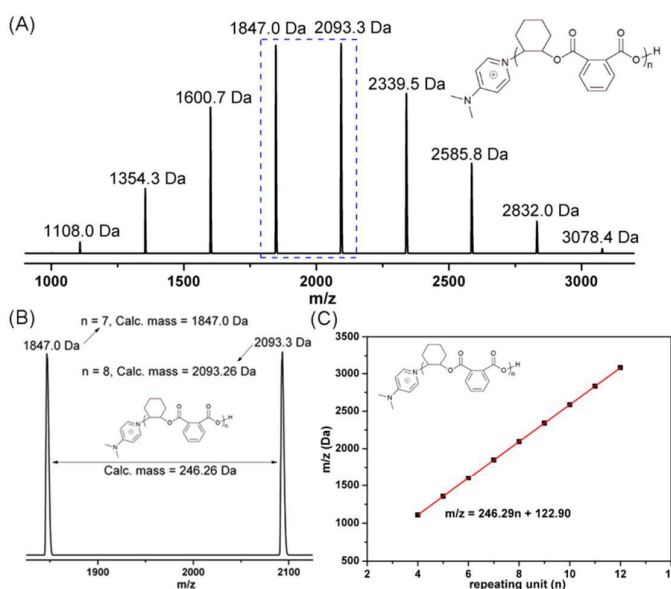
end. In this cyclic period, it was considered that activating and ring-opening of epoxide to alkoxide anion was the rate-determining step (*vide infra* & Figure S13).<sup>15c</sup> Notably, different from cationic mechanism of polyether formation using sole LAs, loose pair interaction<sup>6</sup> of LA and LB suppressed the possibility of alkoxide zwitterionic intermediate attacking epoxides, proven by the result that  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}/\text{CHO}$  cannot gain any polymer at 110 °C even prolonging reaction time.



**Figure 4.** VT  $^1\text{H}$  NMR spectra of the mixture of  $\text{Zn}(\text{C}_6\text{H}_5)_2/\text{DMAP}/\text{PA}/\text{CHO}$  in an NMR tube with the molar ratio of 1:1:1:1 in  $\text{C}_2\text{D}_2\text{Cl}_4$ .



**Scheme 2.** Proposed mechanism schematic illustration of the ROAC of PA/CHO mediated by Lewis pairs.



**Figure 5.** (a) Positive ion MALDI-TOF MS of poly(PA-*alt*-CHO) in a low PA conversion (18%, PA was sublimed three times) precipitated in *n*-hexane without quenching. (b) A detail of blue grid in (a) with calculated and exact masses. (c) The fitting relationship of  $M_n$  vs repeating unit.

Meanwhile, the obtained polyesters were analyzed by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS). Notably, anhydrous *n*-hexane was carefully used to isolate and prepare copolymer samples from reaction mixture without quenching in case that quaternary ammonium moieties of chain ends were substituted by active species (water and acids). As shown in Figure 5, when PA was at a low conversion (18%), only one distribution was observed with DMAP end-capped chains. The great agreement of calculated mass with exact mass suggested that the polymer samples were ionized beforehand.<sup>11d</sup> The distribution exactly consisted of  $n$  [CHO + PA], implying that the epoxide is the preferred monomer to be initiated with  $\text{Zn}(\text{C}_6\text{F}_5)_2/\text{DMAP}$  and the ring-opening of epoxide was rate-determining step in chain propagation. In accordance with the possible mechanism we proposed, DMAP reacted with epoxides rather than anhydrides to generate chain initiating zwitterionic species. When PA conversion was further increased to 44%, two distinct distributions could be observed (Figure S43). Each distribution showed an  $m/z$  interval of 246.26 among the consecutive peaks corresponding to the addition of a [CHO + PA] repeating unit, which is in well agreement with a fully alternating structure. The end group of the intense distribution (86.1%) is  $\omega$ -hydroxyl and DMAP. The low distribution (11.2%) is  $\alpha,\omega$ -di-hydroxyl end-capped, in which the



calculated residue corresponds to the molecular weight of one phthalic acid. The observation confirmed that trace hydrolytic PA can be bifunctional chain initiating species (Scheme S1).<sup>18b</sup> Finally, macrocyclic copolymers formed by intramolecular transesterification were not observed from all of MALDI TOF MS (Figures 5 and S43). The possible reason was ascribed to a big rigid backbone of poly(PA-*alt*-CHO).

## Conclusions

In conclusion, we have introduced here a group of simple and low-toxic Lewis pairs for the synthesis of polyesters by the way of ROAC. At 110 °C, TOFs of Lewis pairs used in this work were as high as 210 h<sup>-1</sup> in bulk, comparable to many metal/ligand complexes. The polarity of solvents, molar ratio and the interaction mode of LA/LB had a great impact on copolymerization rate and chemoselectivity. Furthermore, through optimization of copolymerization conditions, deprotonation side reaction was suppressed by nonpolar solvents and Lewis pairs. Subsequently, an array of structurally diverse polyesters, including semiaromatic and aliphatic polyesters, could be efficiently synthesized by using the versatile Lewis pairs in a controlled manner. The resultant polyesters showed high alternating degree (> 99%) and high regioregularity (for asymmetric epoxides such as PO, ECH and SO). Besides, possible chain initiation and propagation mechanism revealed that epoxides were firstly attacked by Lewis bases, and then carboxylates and alkoxides alternately regenerated, resulting into perfect polyester structures. Therefore, a simple and environmentally benign approach was developed for the preparation of polyesters with diverse geometrical structures.

## Supplementary Information

Characterizations, NMR spectra, additional GPC traces and statistical analysis (PDF)

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## Notes

The authors declare no competing financial interests.



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**Keywords:** ring-opening alternating copolymerization • Lewis pair • polyester • regioselectivity • deprotonation reaction

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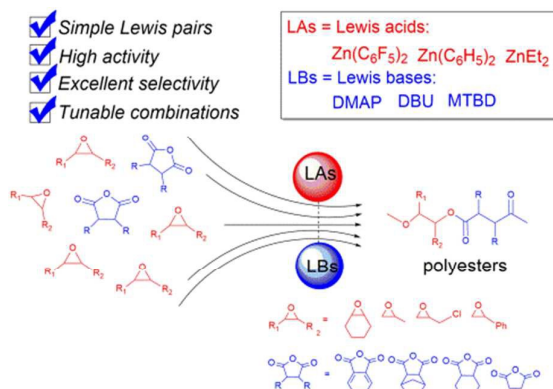
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## Table of contents

## Lewis Pairs for Ring-Opening Alternating Copolymerization of Cyclic Anhydrides and Epoxides

He-Yuan Ji, Bin Wang, Li Pan, Yue-Sheng Li



Simple and low-toxic Lewis pairs were introduced for ring-opening alternating copolymerization of anhydrides and epoxides to diversified polyesters.