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Optically Active Polyketones: Synthesis, Structure, and Reactions

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ABSTRACT: Asymmetric alternating copolymerization of α -olefins (mono-substituted ethenes) with CO provides chiral polyketones in their optically pure forms. Conformation of the polyketones is elucidated in a solution and in a solid state. Studies on the chemical transformation of the functional group, the ketone moiety, are also described.

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Asymmetric synthesis of a chiral polymer from achiral monomer(s) is one of the most challenging stereocontrol in polymer synthesis. Several reports appeared for the asymmetric polymerization of achiral monomers by controlling the newly created chirogenic centers;¹ examples are, asymmetric polymerization of alkyl sorbate,² maleimide,³ epoxide or episulfide,⁴ and so on. The synthesis of a helical polymer by controlling its plus or minus helicity has been another major area of interest in asymmetric polymerization.^{1,5}

We got involved in the asymmetric alternating copolymerization of α -olefins (mono-substituted ethenes) with CO as an extension of our previous studies on the asymmetric carbonylation of olefins.⁶ Copolymerization of ethene with carbon monoxide using transition metal catalysts provides a γ -polyketone, poly(1-oxo-trimethylene), which possesses engineering plastic property, high crystallinity, excellent mechanical property, and chemical resistance. Drent and his coworkers in Shell made great contribution to the development of efficient catalyst for the copolymerization.⁷ Unlike the ethene/CO copolymer, the alternating copolymer of an α -olefin with CO provides a polyketone having stereogenic centers in the main chain. Thus, if the catalyst discriminates one of the two enantiofaces of an α -olefin at the stage of its incorporation, an optically active polyketone, one of the possible two enantiomers of Figure 1, can be produced starting from achiral monomers, an α -olefin and CO. Successful examples of the asymmetric alternating copolymerization of α -olefins with CO appeared in literature in middle 1990's, coincidentally from four research groups including us, employing palladium complexes with chiral ligands.^{8,9} Cationic palladium complexes bearing *cis*-bidentate ligands were the catalysts of choice for the copolymerization and thus

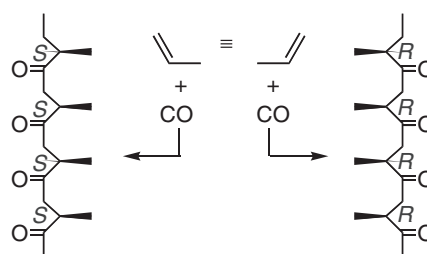


Figure 1. Enantiomers of polyketone.

several chiral *cis*-bidentate ligands have been examined by now.^{10,11}

The α -olefins may be classified into aliphatic 1-alkenes and vinylarenes because these two families of monomers require the use of different types of ligands; phosphorus-based ligands for 1-alkenes and nitrogen-based ligands for vinylarenes, respectively.^{7,10} When an achiral catalyst is employed for the copolymerization, namely under chain-end control, propene/CO alternating copolymer is either atactic or slightly rich in isotactic, while styrene/CO alternating copolymer is rich in syndiotactic. In contrast, catalyst site-control with a chiral ligand provides isotactic alternating copolymer both from propene/CO and styrene/CO. Ideally, a single enantiomer of the chiral catalyst gives the corresponding single enantiomer of an isotactic polyketone.¹¹

SYNTHESIS OF OPTICALLY ACTIVE POLYKETONES

We employed a cationic palladium complex bearing a chiral phosphine-phosphite as a ligand. Using Pd complex **1**, we have obtained completely alternating and completely isotactic poly(propene-*alt*-CO)

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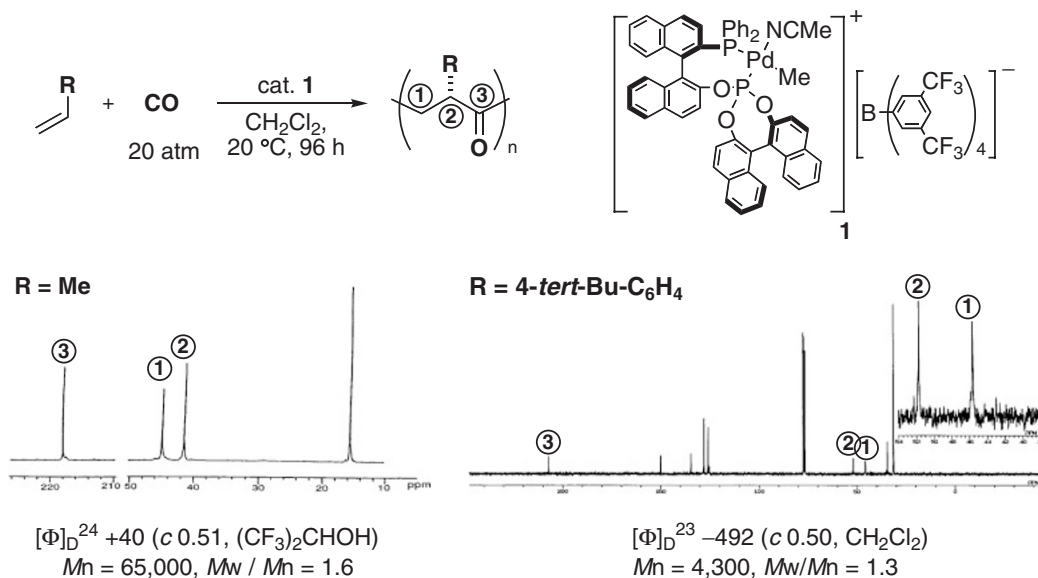
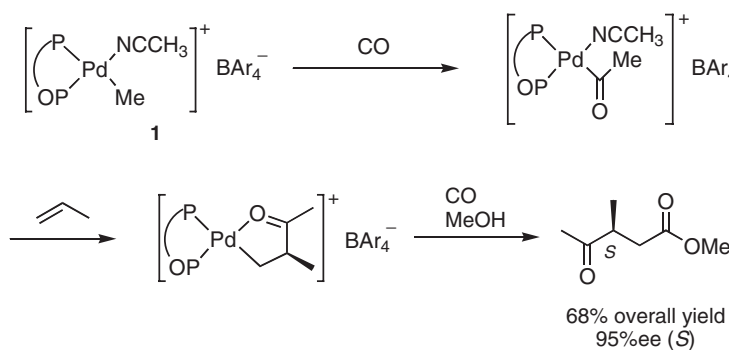


Figure 2. Asymmetric alternating copolymerization of propene/CO and 4-*tert*-butylstyrene/CO.



Scheme 1. Determination of the enantiomeric excess in the asymmetric copolymerization.

and poly(4-*tert*-butylstyrene-*alt*-CO) whose structures were determined by ^{13}C NMR spectroscopy (Figure 2). It should be noted that ^{13}C NMR gives no information about the enantiomeric excess of chiral polymers; in other words, enantiomerically pure (*R*)- or (*S*)-poly(propene-*alt*-CO) and a racemic mixture of (*R*)- and (*S*)-isomers show exactly the same NMR charts. In order to determine the enantiomeric excess, we made an alkylpalladium species which resulted from the first propene insertion, and cleaved the palladium-carbon bond to prove the enantiofacial selection of propene proceeded with over 95% ee (Scheme 1).¹²

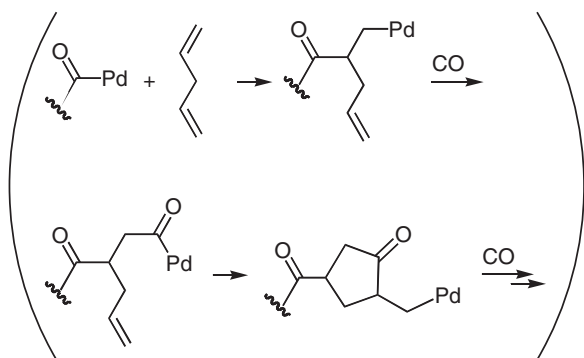
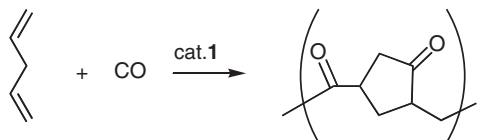
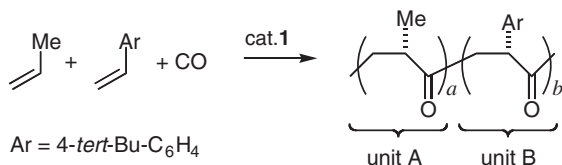
Taking advantage that the catalyst system is applicable to both aliphatic 1-alkene and vinylarene, the asymmetric terpolymerization of propene, 4-*tert*-butylstyrene, and CO was successfully performed (Scheme 2).¹³ The Unit A and B existed in a rather random fashion in the chains and the a/b ratio varied in the range of 0.8–24 depending on the monomer ratio. It is notable that catalyst **1** is the only exception of a phosphorus ligand which is applicable to the vinylarene/CO copolymerization. This unique feature was

attributed to the 1,2-insertion of vinylarene to acylpalladium species, that hardly takes place with other catalysts regardless to nitrogen-ligands or phosphorus-ligands.¹⁴

When an α,ω -diene is used as the alkene moiety, cyclocopolymerization proceeds if the two C–C double bonds are separated with an adequate distance.¹⁵ As an example, the copolymerization of 1,4-pentadiene with CO is described in Scheme 2. A probable cyclization process is also drawn. Complete cyclization has been achieved but the *cis/trans* relative configuration between the two substituents on the cycloalkanone was not controlled.

STRUCTURE OF OPTICALLY ACTIVE POLYKETONES

Due to their isotactic nature, the formation of helical conformation would be anticipated for the optically active polyketones. However, by optical rotation^{8b} or CD spectrum,¹⁶ no evidence has yet been obtained indicating the presence of stable helical conformation



Scheme 2. Terpolymerization of propene/4-*tert*-butylstyrene/CO and cyclocopolymerization of α,ω -diene with CO.

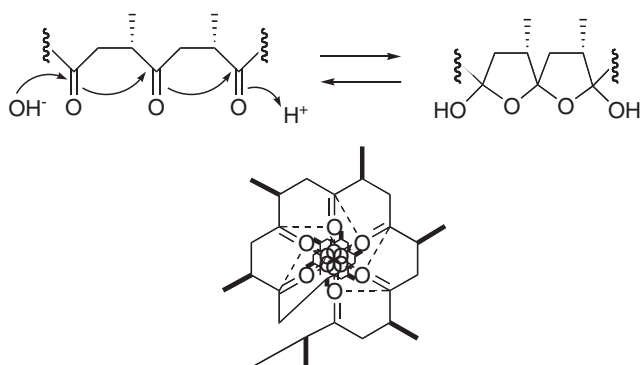


Figure 3. Spiroketal formation of poly(propene-*alt*-CO).

in solution. Meanwhile, extended conformation was estimated for isotactic poly(propene-*alt*-CO) by static light scattering measurement, which might correspond to a helical structure.¹⁶ In one of the possible helical conformations, a carbonyl oxygen of a polyketone comes close to the neighboring carbonyl carbon, which may result in the formation of spiroketal (Figure 3).

In fact, Sen reported the observation of reversible interchange between polyketone and polyspiroketal.^{8b} Spiroketal structure is stable only in the solid state for propene/CO copolymer and pure polyketones were detected when they were dissolved in CDCl₃ as was shown in Figure 2. The spiroketal formation is unique for highly isotactic copolymer mostly generated from propene or other higher aliphatic 1-alkenes. Some of

the polymers maintained the spiroketal structure even in solution. The higher population of spiroketal structure was reported for polyketones bearing fluorine atoms in the side chain,¹⁷ and thus, spiroketal was the single detectable species for an isotactic poly(C₄F₉-CH₂CH=CH₂-*alt*-CO) not only in a solid state but also in a C₆F₆ solution.¹⁸

When an isotactic polyketone bearing azobenzene groups in the side-chains was reprecipitated from CHCl₃/MeOH, a mixture of polyketone and polyspiroacetal units was obtained. It was suggested by CD spectrum that the side-chains were arranged in a helical structure radiated from the spiroketal axis when dissolved in CHCl₃.¹⁹ As shown in Figure 4a, isotactic poly(CH₂=CH(CH₂)₄O-C₆H₄-N=N-Ph-*alt*-CO) of ketal/ketone ratio of 3/1 exhibited the splitted exciton coupling in its CD spectrum. It is noteworthy that the exciton coupling completely invisible in Figure 4b for the polyketone structure in the same solvent as Figure 4a, that is CHCl₃. The pure polyketone structure was generated by dissolving the polymer of ketal/ketone ratio of 3/1 in (CF₃)₂CHOH and then stripping out of the solvent.

In a solid amorphous state, a helical structure is suggested below *T_g* for optically active methylstyrene/1-decene/CO terpolymer but it is not clearly stated whether the spiroketal structure is involved or not.²⁰ A single enantiomer of a side-chain liquid crystalline polyketone forms a chiral nematic phase, that might be attributes to a helical structure of the main chain.²¹

Only one example was reported for crystal structure of the alternating propene-CO copolymer. High molecular weight propene-CO copolymer with random regio- and stereoregularity exhibits elastomeric behavior. A 3₁ helical structure was proposed by an X-ray investigation of an elastic film of the copolymer at 650% elongation.²² For isotactic poly(styrene-*alt*-CO), s(2/1) helical conformation was confirmed by powder X-ray diffraction for optically pure styrene/CO polyketone.²³

A stereocomplex was suggested to be formed from racemic mixture of enantiomeric polyketones derived from propene, 1-butene, and allylbenzene using Pd-(*S*)-Me-DUPHOS and its enantiomer based on the higher *T_m* for the racemic mixture than for enantiomerically pure sample.²⁴ Chiral recognition and the stereocomplexation between two different polyketones, such as (+)-propene/CO and (-)-1-butene/CO, were also confirmed.

REACTIONS OF OPTICALLY ACTIVE POLYKETONES

Chemical transformation of optically active polyketone opens a new route to various functionalized

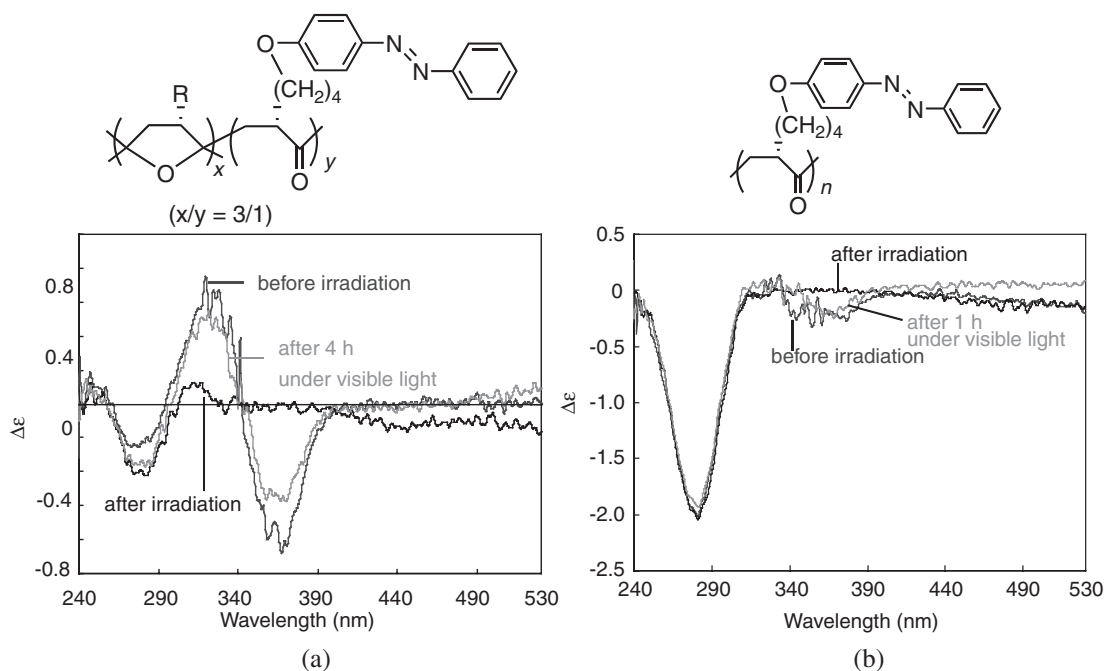
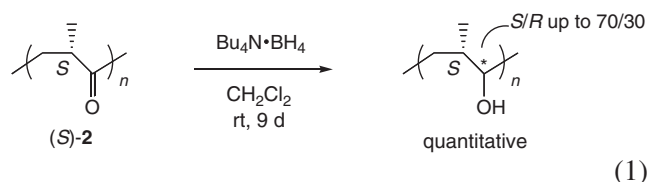


Figure 4. CD spectra of polyspiroketal and polyketone bearing azobenzene side-chains.

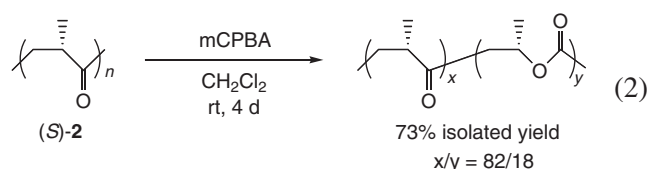
optically active polymers. Apart from optical activity, chemical modification of either non-alternating ethene/CO copolymer or atactic alternating propene/CO copolymer has been extensively studied²⁵ but, before our study, nothing was known about the reaction of optically active, isotactic polyketones. The optically active polyketone derived from propene/CO copolymerization has a chirality center at the α -position of each carbonyl group. It is of much interest whether the configuration is maintained under the reaction conditions. In addition, another interest focuses on the diastereoselectivity when a chirogenic center is newly created in the main-chain though the chemical transformations.

In organic chemistry, diastereoselective reduction of α -chiral carbonyl compounds has been studied since 1950's. Although the arguments have been expanded to more complicated systems, such as α -, β -, and γ -diketones which contain multiple reactive centers, the chemistry still stays in molecular size of so called low molecular weight compounds after half a century. We studied the diastereoselective reduction of poly(propene-*alt*-CO), a γ -polyketone. Using tetrabutylammonium borohydride as a reductant, polyketone (*S*)-**2** was reduced into the corresponding polyol with the *S*/*R* ratio of 70/30 for the absolute configuration of the newly created chirogenic center (eq 1).²⁶ The local structure was determined by the unambiguous synthesis of four diastereomers of 3-methyl-2,5-hexanediol. Comparison of ¹³C NMR spectrum of the polyol with those of the model diols indicated that no epimerization occurred on the α -carbon atoms. The

S-selectivity contradicts to the conventional Cram-selectivity with which *R*-configuration is predicted from (*S*)-**1**. Considering that free-rotation around the C–C bond between the carbonyl carbon and the α -carbon is a prerequisite for the Cram rule, the present *S*-selectivity should be attributed to the restricted free rotation around the C–C bond.

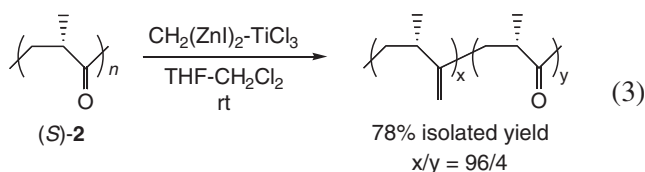


Baeyer-Villiger oxidation of (*S*)-**2** with *m*-chloroperbenzoic acid provided poly(ketone/ester) in a ratio of ketone/ester = 82/18 in 73% isolated yield (eq 2).²⁷ An ester unit likely exists to distribute randomly in the product rather than to form a block copolymer of a polyketone and a polyester. This was suggested by methanolysis of the product polymer to give oligomers rather than methyl 3-hydroxybutyrate. Because poly((*R*)-3-hydroxybutyrate) (PHB), the ester part of the current polymer, is a well-known biodegradable polymer,²⁸ further improvement of this oxidation is highly desired.



Addition of a carbanion to the carbonyl group also

successfully proceeded without epimerization at the α -carbon although carbanions may possibly cause side reactions, such as deprotonation of α -proton followed by epimerization or aldol reaction. We reported the methylenation of the polyketones (*S*)-**2** using dizinc-titanium reagent, $\text{CH}_2(\text{ZnI})_2\text{-TiCl}_3$, to give the corresponding methylenated polymer (eq 3).²⁹ The reaction proceeded without any significant epimerization and the product was highly isotactic. This was confirmed by comparison of ¹³C NMR spectrum of the product polymer with that of an atactic analog. The products, a new class of hydrocarbon polymers with main-chain chirality, are attainable only by this transformation but not by any other methods, such as ring-opening polymerization of 2-alkyl-1-methylenecyclopropanes.



CONCLUSIONS

Unlike the polymerization of vinyl monomers, not only tacticity but also chirality becomes a critical issue of stereocontrol in the alternating copolymerization of α -olefins with CO. Employing chiral palladium catalyst **1**, asymmetric copolymerization with CO was performed both with propene and with 4-*tert*-butylstyrene. The polyketone itself did not show any evidence for the higher order structure but helical conformation was suggested for polyspiroketal which arise from the isomerization of the polyketone. Chemical transformation of the optically active polyketone, such as reduction, oxidation, and methylenation provided several new types of new polymers with optical activity. Through out the studies, we confirmed that the new methodologies continuously developed in the field of organic synthesis can be effectively applied in the field of polymer synthesis.

REFERENCES

1. a) Y. Okamoto and T. Nakano, *Chem. Rev.*, **94**, 349 (1994).
b) T. Nakano and Y. Okamoto, *Chem. Rev.*, **101**, 4013 (2001).
2. a) P. Pino, *Adv. Polym. Sci.*, **4**, 393 (1965).
b) G. Natta, M. Farina, and M. Donati, *Makromol. Chem.*, **112**, 220 (1961).
3. a) Y. Okamoto, T. Nakano, H. Kobayashi, and K. Hatada, *Polym. Bull.*, **25**, 5 (1991).
b) T. Oishi, H. Yamasaki, and M. Fujimoto, *Polym. J.*, **23**, 795 (1991).
4. a) N. Spassky, A. Momtaz, A. Kassamaly, and M. Sepulchre, *Chirality*, **4**, 295 (1992).
b) N. Spassky, M. Wisniewski, C. Pluta, and A. LeBorgne, *Makromol. Chem. Phys.*, **197**, 2627 (1996).
5. M. M. Green, J.-W. Park, T. Sato, A. Teramoto, S. Lifson, R. L. B. Selinger, and J. V. Selinger, *Angw. Chem. Int. Ed.*, **38**, 3138 (1999).
6. a) N. Sakai, S. Mano, K. Nozaki, and H. Takaya, *J. Am. Chem. Soc.*, **115**, 7033 (1993).
b) K. Nozaki, N. Sakai, T. Nanno, T. Higashijima, S. Mano, T. Horiuchi, and H. Takaya, *J. Am. Chem. Soc.*, **119**, 4413 (1997).
7. E. Drent and P. H. M. Budzelaar, *Chem. Rev.*, **96**, 663 (1996).
8. Propene/CO: a) S. Bronco, G. Consiglio, R. Hutter, A. Batistini, and U. W. Suter, *Macromolecules*, **27**, 4436 (1994).
b) Z. Jiang and A. Sen, *J. Am. Chem. Soc.*, **117**, 4455 (1995).
c) K. Nozaki, N. Sato, and H. Takaya, *J. Am. Chem. Soc.*, **117**, 9911 (1995).
9. Styrene/CO: a) M. Brookhart, M. I. Wagner, G. G. A. Balavoine, and H. A. Haddou, *J. Am. Chem. Soc.*, **116**, 3641 (1994).
b) Z. Jiang, S. E. Adams, and A. Sen, *Macromolecules*, **27**, 2694 (1994).
10. C. Bianchini and A. Meli, *Coord. Chem. Rev.*, **225**, 35 (2002).
11. a) K. Nozaki, in "Catalytic Synthesis of Alkene-Carbon Monoxide Copolymers and Cooligomers," A. Sen, Ed., Kluwer Academic Publishers, Dordrecht, 2003, p. 217.
b) K. Nozaki and T. Hiyama, *J. Organomet. Chem.*, **57**, 253 (1999).
c) K. Nakano, N. Kosaka, T. Hiyama, and K. Nozaki, *Dalton Trans*, **2003**, 3985.
12. K. Nozaki, N. Sato, Y. Tonomura, M. Yasutomi, H. Takaya, and T. Hiyama, *J. Am. Chem. Soc.*, **119**, 12779 (1997).
13. K. Nozaki, Y. Kawashima, K. Nakamoto, and T. Hiyama, *Macromolecules*, **32**, 5168 (1999).
14. a) K. Nozaki, H. Komaki, Y. Kawashima, T. Hiyama, and T. Matsubara, *J. Am. Chem. Soc.*, **123**, 534 (2001).
b) J. A. Iggo, Y. Kawashima, J. Liu, T. Hiyama, and K. Nozaki, *Organometallics*, **22**, 5418 (2003).
15. a) K. Nozaki, N. Sato, K. Nakamoto, and H. Takaya, *Bull. Chem. Soc. Jpn.*, **70**, 659 (1997).
b) S. L. Borkowsky and R. W. Waymouth, *Macromolecules*, **29**, 6377 (1996).
16. a) N. Kosaka, K. Nozaki, T. Hiyama, M. Fujiki, N. Tamai, and T. Matsumoto, *Macromolecules*, **36**, 6884 (2003).
b) B. Sesto, S. Bronco, E. L. Gindro, and G. Consiglio, *Makromol. Chem. Phys.*, **202**, 2059 (2001).
17. K. Nozaki, F. Shibahara, S. Elzner, and T. Hiyama, *Can. J. Chem.*, **79**, 593 (2001).
18. T. Fujita, K. Nakano, M. Yamashita, and K. Nozaki, submitted for publication.
19. N. Kosaka, T. Oda, T. Hiyama, and K. Nozaki, *Macromolecules*, **37**, 3159 (2004).
20. B. T. Muellers, J.-W. Park, M. S. Brookhart, and M. M. Green, *Macromolecules*, **34**, 573 (2001).
21. a) K. Nozaki, Y. Kawashima, T. Oda, T. Hiyama, K. Kanie, and T. Kato, *Macromolecules*, **35**, 1140 (2002).

- b) Y. Kawashima, K. Nozaki, T. Hiyama, M. Yoshio, K. Kanie, and T. Kato, *J. Polym. Sci., Part A: Polym. Chem.*, **41**, 3556 (2003).
22. a) A. S. Abu-Surrah, R. Wursche, B. Rieger, G. Eckert, and W. Pechhold, *Macromolecules*, **29**, 4806 (1996).
b) Y. K. Godovsky, E. V. Konyukhova, S. N. Chvalun, V. M. Neverov, A. S. Abu-Surrah, and B. Rieger, *Macromol. Chem. Phys.*, **200**, 2636 (1999).
23. a) S. Bruckner, C. DeRosa, P. Corradini, W. Porzio, and A. Musco, *Macromolecules*, **29**, 1535 (1996).
b) C. DeRosa, *Macromolecules*, **30**, 5494 (1997).
24. Z. Jiang, M. T. Boyer, and A. Sen, *J. Am. Chem. Soc.*, **117**, 7037 (1995).
25. A. Sen, *CHEMTECH*, 48 (1986).
26. K. Nozaki, N. Kosaka, S. Muguruma, and T. Hiyama, *Macromolecules*, **33**, 5340 (2000).
27. N. Kosaka, T. Hiyama, and K. Nozaki, *Macromolecules*, **37**, 4484 (2004).
28. a) H.-M. Müller and D. Seebach, *Angew. Chem., Int. Ed.*, **32**, 477 (1993).
b) K. Sudesh, H. Abe, and Y. Doi, *Prog. Polym. Sci.*, **25**, 1503 (2000).
29. a) K. Nozaki, N. Kosaka, V. M. Graubner, and T. Hiyama, *Macromolecules*, **34**, 6168 (2001).
b) K. Nozaki, N. Kosaka, V. M. Graubner, and T. Hiyama, *Polymer J.*, **34**, 376 (2002).
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Her research interest concerns the development of homogeneous catalysis for stereocontrol in organic synthesis and polymer synthesis. Her accomplishments include the Inoue Research Award for Young Scientists (1992), Pfizer Award for Young Chemists in Synthetic Organic Chemistry, Japan (1994), the Chemical Society of Japan Award for Young Chemists (1998), Award for outstanding paper in Polymer Journal (2003), OMCOS prize in organometallic chemistry (2003), and SPSJ Wiley Award (2004). She is on the international advisory board of Journal of Polymer Science A: Polymer Chemistry, Dalton Transactions of Royal Society of Chemistry, Green Chemistry and of the International Symposium on Homogeneous Catalysis.