

Design of a Dynamic Polymer Interface for Chiral Discrimination

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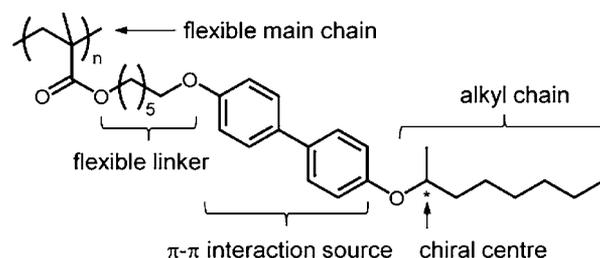
S Supporting Information

ABSTRACT: Enantioselective wetting of a chiral polymer film was demonstrated. The contact angle of chiral liquids on the film was strongly dependent on their chirality although their physical properties including surface tension were identical. Such wetting behavior resulted from the enantioselective surface reorganization involving local conformational change of the polymer chains at the liquid interface. The concept of “dynamic interface for chiral discrimination” has possible potential for the development of materials capable of chiral sensing, optical resolution, and asymmetric synthesis.

Molecular chirality is one of the keys in various biological events in living systems. Thus, great effort has been expanded to develop artificial polymers and molecules that are capable of chiral discrimination using biomimetic and/or supramolecular concepts.¹ However, most of the polymers and molecules investigated have been studied in the solution state. If one desires to solidify a polymer or molecule and use it as a material for chiral sensing, optical resolution and asymmetric synthesis, the surface properties of the materials should be taken into account. This is simply because the material surface is in contact with a chiral liquid and a selective interaction with one enantiomer occurs at the liquid interface. For such materials development involving surface engineering, one of the challenging issues is to achieve enantioselective wetting, where the surface properties vary in response to chirality of the surrounding liquid. Until now, such wetting has not been realized in the absence of an auxiliary² due to the difficulty of amplifying molecular chiral discrimination to appear as a macroscopic event.^{2,3} Thus, the fabrication of a surface for enantioselective wetting remains challenging, although it should find broad applications in chiral selectors,⁴ biomolecular scaffolds,⁵ microfluidic devices⁶ and so forth. In this communication, we report the first instance of the enantioselective wetting of a chiral polymer film. Our successful strategy utilizes two concepts; surface reorganization of the polymer film and an induced chirality of the polymer side chain.

It has been widely accepted that the surface structure of polymer films varies in response to their surrounding environment to minimize the interfacial free energy.⁷ For example, the surface of a film of an amphiphilic block copolymer was covered with the hydrophobic component in air or vacuum. However, once the film was immersed into water, the surface turns to be hydrophilic due to the preferential segregation of the hydrophilic component at the water interface.⁸ Such a surface reorganization was also found for a

Scheme 1. Chemical Structure of Chiral Polymers Designed and Synthesized in This Study



film of simple poly(*n*-alkyl methacrylate)s, in which the ester bond behaves as the hydrophilic component.⁹ This should be the case even though a chiral molecule is applied to a polymer surface as a liquid. If the surface can discriminate the chirality, the wettability should be eventually different between two enantiomeric liquids. To realize such enantioselectivity, the polymer should be chiral and possess a high capability of the chiral discrimination.

On the basis of these considerations, we designed a chiral polymer, as shown in Scheme 1 (*S*-P and *R*-P). The polymer contains four important units; the main chain of methacrylate, alkyl linkers, biphenyl moieties, and alkyl chains having a chiral center. A methacrylate main chain was chosen because of its flexibility, resulting in a surface reorganization responding to environmental change. To preserve the flexibility of the main chains, alkyl linkers were inserted between the main chain and the biphenyl moieties. The biphenyl moiety works as a π - π interaction source, leading to the arrangement of the side chains.¹⁰ The alkyl chain having a chiral center provides a chirally twisted structure to the side-chain arrangement, the so-called induced chirality. Such induced chirality has often been observed for helical polymers, supramolecular gels, liquid crystals, and Langmuir–Blodgett films,¹¹ and leads to high enantioselectivity.^{4,a,b,12}

S-P and *R*-P were synthesized in four steps (see the Supporting Information, SI). The alkyl chain with a chiral center was introduced to 4,4'-biphenol by a Mitsunobu reaction using (*R*)- or (*S*)-2-octanol. Subsequently, 2-bromo-1-hexanol as a flexible spacer was introduced by a Williamson etherification and the resultant hydroxyl group was then allowed to react with methacryloyl chloride, leading to a chiral monomer. Finally, *S*-P or *R*-P was obtained by a free radical polymerization of the corresponding monomers. The number-average

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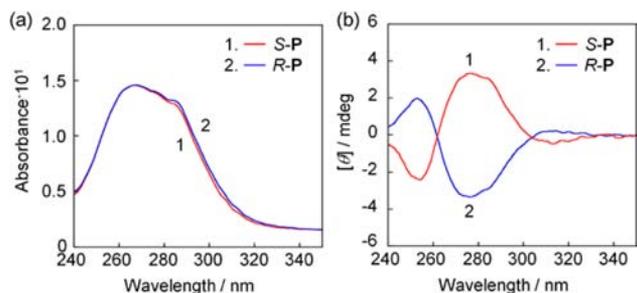


Figure 1. (a) UV-vis and (b) CD spectra for the S-P and R-P films on quartz glass substrates.

molecular weight and polydispersity index were determined to be 18k and 1.8 for S-P, and 18k and 2.3 for R-P, by gel permeation chromatography using poly(methyl methacrylate) as a standard.

Films of the polymers were prepared on quartz glass substrates and silicon substrates with a native oxide layer by a spin-coating method from *n*-hexane solution of each of the polymers at a concentration of 1.0 wt %. The film thickness was determined to be typically 53 nm by ellipsometry. Figure 1 shows ultraviolet-visible (UV-vis) and circular dichroism (CD) spectra for the S-P and R-P films. UV-vis spectra for these films were identical and were characterized by an absorption band centered at 265 nm being assignable to the π - π^* transition of the biphenyl moiety in the side chain of the polymer. The maximum absorption wavelength (λ_{max}) observed for both films was shorter than that for the corresponding polymers in the solution state ($\lambda_{\text{max}} = 270$ nm) where the biphenyl moieties were isolated from each other (see Figure S4 in the SI). This makes it clear that the biphenyl moieties in the polymer side chain form an *H*-like aggregation in both S-P and R-P films. Interestingly, CD spectra for the S-P and R-P films showed an induced CD signal depending on the molecular chirality. The spectral patterns remain unchanged by rotating the films around the light beam axis, confirming that there was no contribution from a linear dichroism signal (see Figure S5 in the SI). These results lead to an assumption that the polymer provides an induced chirality based on a chiral arrangement of biphenyl moieties through the *H*-like stacking and its handedness is imposed by the molecular chirality.

Enantioselective surface properties of the films were investigated by contact angle measurements using (S)- and (R)-1,2-propanediols (S-L and R-L) as probe liquids, which are important building block as versatile chiral synthons for asymmetric synthesis and thus a rapid detection of their chirality is required.¹³ Panel a of Figure 2 shows the time (*t*) dependence of the contact angle (θ) of the droplets of S-L and R-L on the S-P film. The initial θ value for the S-L droplet was 63° and did not change over the time after being placed. In the case of R-L, on the other hand, the θ exponentially decreased with increasing time and reached a constant value of 41° after 20 s. That is, the θ value at *t* = 30 s was smaller for R-L than for S-L, as shown in Figure 2b. Importantly, opposite behaviors were observed for the R-P film. The θ value for the S-L droplet was time-dependent while that of R-L was not (see Figure S7 in the SI). The θ values for R-L and for S-L at *t* = 30 s were 63° and 41°, respectively. These results clearly indicate that the polymer films possess enantioselective surface properties, which were also confirmed by using 1,3-butanediol as a probe liquid (see Figure S8 in the SI).

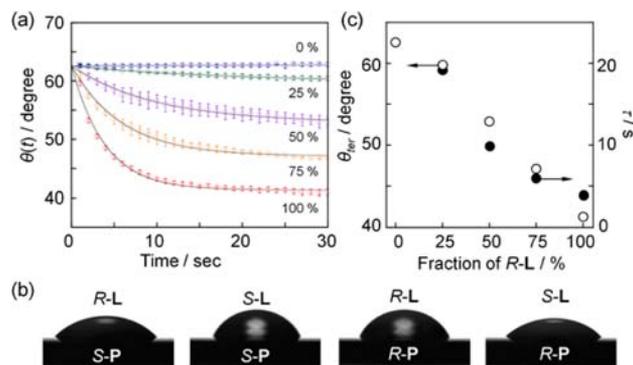


Figure 2. (a) Time dependence of the contact angle of a mixture of S-L and R-L with various R-L fractions on the S-P film. Open circles and solid lines denote the experimental data and best-fit curves using eq 1. (b) Photograph showing the S-L and R-L droplets on the S-P and R-P films after 30 s. (c) Correlation between the θ_{ter} and τ values and the R-L fraction.

The above-mentioned results motivated us to examine the contact angle of a mixture of S-L and R-L with various ratios. As shown in Figure 2a, the extent of the time dependence of the contact angle was striking with a higher fraction of R-L. To quantify the behaviors, the θ -*t* plot was fitted by the following equation:^{9e}

$$\theta(t) = (\theta_{\text{ini}} - \theta_{\text{ter}}) \exp(-t/\tau) + \theta_{\text{ter}} \quad (1)$$

where θ_{ini} , θ_{ter} and τ are the initial θ at *t* = 0, the terminal θ , and the time constant for the θ decay, respectively. Curve-fitting for all plots provided a good correlation coefficient ($r^2 > 0.98$). Panel c of Figure 2 shows the composition dependence of θ_{ter} and τ . Both θ_{ter} and τ were proportional to the R-L fraction.

The origin of the θ_{ter} difference between S-L and R-L droplets on the S-P film is discussed. According to Young's relation, the contact angle can be given by

$$\theta_{\text{ter}} = \cos^{-1}\{(\gamma_{\text{s}} - \gamma_{\text{sl}})/\gamma_{\text{l}}\} \quad (2)$$

where γ_{s} , γ_{sl} and γ_{l} are the tensions at the solid/gas, solid/liquid and liquid/gas interfaces, respectively. Here, the γ_{s} value was common for the two cases because the same film was used under controlled temperature and humidity. Also, the γ_{l} values of S-L and R-L are identical at 48 mN m⁻¹ due to their enantiomeric chemical structures.¹⁴ Thus, the θ_{ter} difference between S-L and R-L droplets on the S-P film must be related to the γ_{sl} value. That is, the interfacial structures of S-P with S-L and R-L were different from each other.

To confirm the above-mentioned hypothesis, the surface of the film, which was immersed into the chiral liquid, was characterized by atomic force microscopy (AFM) using the intermittent contact mode at room temperature. Figure 3 shows the surface morphology and corresponding cross-sectional profiles of the S-P films. The surface of the original S-P film was relatively flat with a root-mean square roughness (R_{RMS}) of 2.0 ± 0.4 nm. No substantial change was observed after immersing the film into S-L ($R_{\text{RMS}} = 2.1 \pm 0.5$ nm). However, after the immersion in R-L, the film surface became rougher, resulting in the R_{RMS} value of 3.1 ± 0.5 nm. These results indicate that the surface morphology of the S-P film was changed by contact with R-L but not with S-L, as a result of the change in the aggregation states of polymer chains.

It is well-known that the contact angle is affected by the surface roughness of a film even on the nanometer scale.¹⁵ The

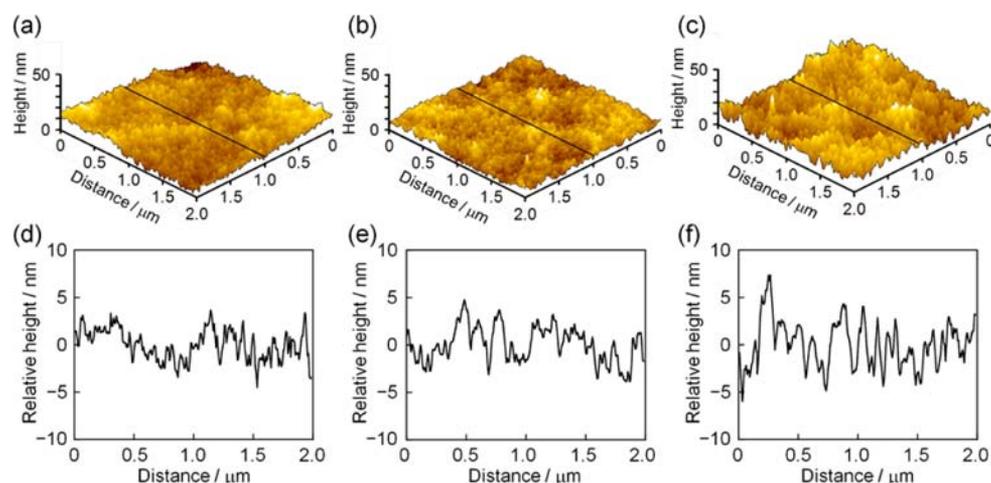


Figure 3. (a–c) Surface morphology and (d–f) cross-sectional profiles along the solid lines shown in panels a–c obtained for the S-P film under (a and d) the ambient air, (b and e) S-L, and (c and f) R-L.

roughness effect has been discussed on the basis of the two major classical models of Wenzel and Cassie–Baxter. When a droplet completely contacts with a surface of a given material over their mutual interface, the contact angle on a rough surface can be expressed by Wenzel's equation. This equation predicts that the apparent contact angle becomes smaller with increasing surface roughness when the θ value for a flat surface is less than 90° . Thus, a plausible explanation for the reason why the contact angle on the S-P film was smaller for R-L than for S-L is the roughness effect. To confirm whether this is the case, we estimated to what extent the θ value of R-L on the S-P film became smaller by the surface roughness (see the SI). As a result, it could be 61° , being much larger than the experimental value of 41° . Also, the experimental value cannot be rationalized by Cassie's equation, where a probe droplet partially contacts the top of surface protrusions with an air gap. In this case, the apparent contact angle on the rough surface (the R-L/S-P interface in our case) is always larger than that on the flat surface (the S-L/S-P interface). Thus, the contact angle difference for S-L and R-L shown in Figure 2 can hardly be explained in terms of the surface roughness of the film. This leads to an idea that aggregation states of chains in the S-P film can be altered only by R-L.

To examine local conformation of the polymer chains at the chiral liquid interface, sum frequency generation (SFG) vibrational spectroscopy, which currently provides the best depth resolution among available techniques, was performed. Figure 4 shows SFG spectra for the S-P film at air, S-L, and R-L interfaces. Here, the measurements were carried out with a light polarization combination of ssp (SF output, visible input, and infrared input). In this case, information on dipoles, or functional groups, along the direction normal to the interface is accessible.^{9d,16} For the original film, signals from the symmetric and antisymmetric C–H stretching vibrations of the methylene groups were clearly observed at 2852 and 2930 cm^{-1} , respectively. Signals assignable to the symmetric and antisymmetric C–H stretching vibrations of the methyl groups were also observed at 2866 and 2948 cm^{-1} , respectively. After immersing the S-P film in S-L, the SFG spectrum was almost unchanged. On the other hand, when the film was immersed into R-L, the intensity of the signals from the methylene groups became weaker. Instead, a signal from the antisymmetric C–H stretching vibration of the methylene groups next to the oxygen

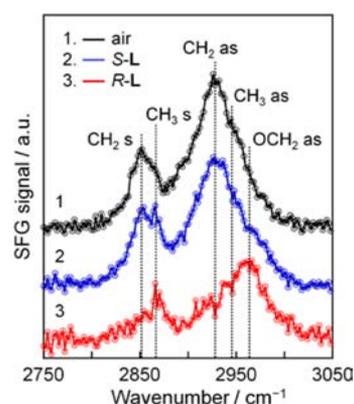


Figure 4. SFG spectra for the S-P film at air, S-L, and R-L interfaces, obtained with an ssp polarization combination.

atom in the ester and the ether bonds evolved.^{9b} This spectral change is quite reasonable if the side chains of S-P segregate to the R-L phase as a result of formation of an attractive interaction between the carbonyl group of S-P and the hydroxyl group in R-L.

In fact, it has been reported that the change in the interfacial conformation of poly(*n*-alkyl methacrylate)s upon contacting water was induced by hydrogen bonding between the carbonyl groups in the polymer side chain and water.⁹ Thus, the enantioselective wetting seen here is associated with a surface reorganization via the local conformational change of polymer chains.¹⁷ If so, a decrease in the contact angle of R-L on the S-P film with increasing time (Figure 2a) should reflect the conformational change. It is noteworthy that the S-P film, after immersion in R-L and then being dried with a nitrogen flow, shows the same time dependency in the contact angle of S-L and R-L as that observed for the original film (see Figure S9 in the SI). This suggests that the local conformation of polymer chains at the R-L interface returned to the original one when R-L was removed. Taking into account that the driving force for the local conformation change of chains is the formation of noncovalent bonds such as hydrogen bonding, the reversible change in the surface properties depending on the presence or absence of the liquid can be understood.¹⁸

We have demonstrated enantioselective surface properties of films of a chiral polymer by contact angle measurements using

chiral aliphatic diols as a probe liquid. The contact angle varies over the range of 41° to 63°, depending on the chirality of the liquid. This is based on the enantioselective surface reorganization of the polymer chains, which is induced by hydrogen bonding between the carbonyl group in the polymer and the hydroxyl group in the liquid. The present results illustrate the utilization of the polymer film for the determination of chirality by observing the wetting behaviors. The concept, for which we propose the name “dynamic interface for chiral discrimination” has possible potential for the development of chiral materials, leading to a breakthrough in the field of chemistry and materials science dealing with chirality.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details and additional characterization data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

- (1) (a) James, T. D.; Sandanayake, K. R. A. S.; Shinkai, S. *Nature* **1995**, *374*, 345–347. (b) Kubo, Y.; Maeda, S.; Tokita, S.; Kubo, M. *Nature* **1996**, *382*, 522–524. (c) Yashima, E.; Maeda, K.; Okamoto, Y. *Nature* **1999**, *399*, 446–451. (d) Mizuno, Y.; Aida, T.; Yamaguchi, K. *J. Am. Chem. Soc.* **2000**, *122*, 5278–5285. (e) Zhu, L.; Anslyn, E. V. *J. Am. Chem. Soc.* **2004**, *126*, 3676–3677. (f) Yoshizawa, M.; Tamura, M.; Fujita, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 3874–3876. (g) Hembury, G. A.; Borovkov, V. V.; Inoue, Y. *Chem. Rev.* **2008**, *108*, 1–73. (h) Shundo, A.; Labuta, J.; Hill, J. P.; Ishihara, S.; Ariga, K. *J. Am. Chem. Soc.* **2009**, *131*, 9494–9495.
- (2) Rapp, M.; Ducker, W. A. *J. Am. Chem. Soc.* **2010**, *132*, 18051–18053.
- (3) (a) Ariga, K.; Richards, G. J.; Ishihara, S.; Izawa, H.; Hill, J. P. *Sensors* **2010**, *10*, 6796–6820. (b) Qing, G.; Sun, T. *Adv. Mater.* **2011**, *23*, 1615–1620.
- (4) (a) Okamoto, Y.; Yashima, E. *Angew. Chem., Int. Ed.* **1998**, *37*, 1020–1043. (b) Aoki, T.; Kobayashi, Y.; Kaneko, T.; Oikawa, E.; Yamamura, Y.; Fujita, Y.; Teraguchi, M.; Nomura, R.; Masuda, T. *Macromolecules* **1999**, *32*, 79–85. (c) Hart, B. R.; Rush, D. J.; Shea, J. J. *J. Am. Chem. Soc.* **2000**, *122*, 460–465. (d) Rmaile, H. H.; Schlenoff, J. B. *J. Am. Chem. Soc.* **2003**, *125*, 6602–6603. (e) Buono, A. M.; Immediata, I.; Rizzo, P.; Guerra, G. *J. Am. Chem. Soc.* **2007**, *129*, 10992–10993.
- (5) (a) Murata, H.; Chang, B.-J.; Prucker, O.; Dahm, M.; Rühle, J. *Surf. Sci.* **2004**, *570*, 111–118. (b) Anderson, D. G.; Levenberg, S.; Langer, R. *Nat. Biotechnol.* **2004**, *22*, 863–866. (c) Place, E. S.; Evans, N. D.; Stevens, M. M. *Nat. Mater.* **2009**, *8*, 457–470. (d) Zhang, M.; Qing, G.; Sun, T. *Chem. Soc. Rev.* **2012**, *41*, 1972–1984.
- (6) (a) Zhao, B.; Moore, J. S.; Beebe, D. J. *Science* **2001**, *291*, 1023–1026. (b) Whitesides, G. M. *Nature* **2006**, *442*, 368–373. (c) Tanret, I.; Mangelings, D.; Vander Heyden, Y. *Curr. Pharm. Anal.* **2009**, *5*, 101–111. (d) Kim, B. Y.; Yang, J.; Gong, M.; Flachsbar, B. R.; Shannon, M. A.; Bohn, P. W.; Sweedler, J. V. *Anal. Chem.* **2009**, *81*, 2715–2722.
- (7) Andrade, J. D. *Surface and Interfacial Aspects of Biomedical Polymers*; Plenum Press: New York, 1985; pp 249–292.
- (8) (a) Senshu, K.; Yamashita, S.; Ito, M.; Hirao, A.; Nakahama, S. *Langmuir* **1995**, *11*, 2293–2300. (b) Pike, J. K.; Ho, T.; Wynne, K. J. *Chem. Mater.* **1996**, *8*, 856–860. (c) Rangwalla, H.; Schwab, A. D.; Yurdumakan, B.; Yablon, D. G.; Yaganeh, M. S.; Dhinojwala, A. *Langmuir* **2004**, *20*, 8625–8633.
- (9) (a) Li, G.; Ye, S.; Morita, S.; Nishida, T.; Osawa, M. *J. Am. Chem. Soc.* **2004**, *126*, 12198–12199. (b) Chen, C.; Clarke, M. L.; Wang, J.; Chen, Z. *Phys. Chem. Chem. Phys.* **2005**, *7*, 2357–2363. (c) Chen, Z. *Polym. Int.* **2007**, *S6*, 577–587. (d) Tateishi, Y.; Kai, N.; Noguchi, H.; Uosaki, K.; Nagamura, T.; Tanaka, T. *Polym. Chem.* **2010**, *1*, 303–311. (e) Horinouchi, A.; Atarashi, H.; Fujii, Y.; Tanaka, K. *Macromolecules* **2012**, *45*, 4638–4642.
- (10) des Barrio, J.; Tejedor, R. M.; Chinelatto, L. S.; Sánchez, C.; Piñol, M.; Oriol, L. *J. Mater. Chem.* **2009**, *19*, 4922–4930.
- (11) (a) Green, M. M.; Peterson, N. C.; Sato, T.; Teramoto, A.; Cook, R.; Lifson, S. *Science* **1995**, *268*, 1860–1866. (b) Akagi, K.; Piao, G.; Kaneko, S.; Sakamaki, K.; Shirakawa, H.; Kyotani, M. *Science* **1998**, *282*, 1683–1686. (c) Oda, R.; Huc, I.; Schmutz, M.; Candau, S. J.; MacKintosh, F. C. *Nature* **1999**, *399*, 566–569. (d) Yuan, J.; Liu, M. *J. Am. Chem. Soc.* **2003**, *125*, 5051–5056. (e) Dolain, C.; Jiang, H.; Léger, J.-M.; Guionneau, P.; Huc, I. *J. Am. Chem. Soc.* **2005**, *127*, 12943–12951. (f) Smith, D. K. *Chem. Soc. Rev.* **2009**, *38*, 684–694.
- (12) (a) Okamoto, Y.; Kawashima, M.; Hatada, K. *J. Chromatogr.* **1986**, *363*, 173–186. (b) Shundo, A.; Sakurai, T.; Takafuji, M.; Nagaoka, S.; Ihara, H. *J. Chromatogr. A* **2005**, *1073*, 169–174. (c) Michinobu, T.; Shinoda, S.; Nakanishi, T.; Hill, J. P.; Fujii, K.; Player, T. N.; Tsukube, H.; Ariga, K. *J. Am. Chem. Soc.* **2006**, *128*, 14478–14479. (d) Jintoku, H.; Takafuji, M.; Oda, R.; Ihara, H. *Chem. Commun.* **2012**, *48*, 4881–4883.
- (13) Kometani, T.; Toide, H.; Daikaji, Y.; Goto, M. *J. Biosci. Bioeng.* **2001**, *91*, 525–527.
- (14) Rafati, A. A.; Ghasemian, E.; Abdolmaleki, M. *J. Chem. Eng. Data* **2008**, *53*, 1944–1949.
- (15) (a) Youngblood, J. P.; McCarthy, T. J. *Macromolecules* **1999**, *32*, 6800–6806. (b) Öner, D.; McCarthy, T. J. *Langmuir* **2000**, *16*, 7777–7782. (c) Miwa, M.; Nakajima, A.; Fujishima, A.; Hashimoto, K.; Watanabe, T. *Langmuir* **2000**, *16*, 5754–5760. (d) Feng, X.; Jiang, Lei. *Adv. Mater.* **2006**, *18*, 3063–3078.
- (16) (a) Zhu, X. D.; Suhr, H.; Shen, Y. R. *Phys. Rev. B: Condens. Matter* **1987**, *35*, 3047–3050. (b) Shen, Y. R. *Nature* **1989**, *337*, 519–525.
- (17) CD spectra for the S-P films immersed in S-L and R-L revealed that the presence of S-L and R-L did not affect the original spectrum of the film. Postulating that the CD spectra mostly reflect the bulk information, it is conceivable that the conformational change of the polymer chains occurs in close proximity to the liquid interface. See Figure S6 in the SI.
- (18) The bulk glass transition temperature (T_g) of both S-P and R-P determined by differential scanning calorimetry was 310 K (see Figure S3 in the SI). This temperature was higher than the temperature at which the contact angle and SFG measurements were made, 298 K. However, given that T_g at the film surface was lower than the bulk T_g and/or that chiral liquid acts as a plasticizer for the corresponding chiral polymer, the segmental motion can be attained at the liquid interface even at 298 K. Actually, such has been reported for poly(methyl methacrylate). See ref 9e and the following: Fujii, Y.; Nagamura, T.; Tanaka, K. *J. Phys. Chem. B* **2010**, *114*, 3457–3460.