Nanostructured Supramolecular Block Copolymers Based on Polydimethylsiloxane and Polylactide

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Ⓢ *Supporting Information*

ABSTRACT: Hierarchical self-assembly has been demonstrated with diblock copolymers comprising poly(dimethylsiloxane) (PDMS) and poly(lactide) (PLA) with supramolecular, 4-fold hydrogen-bonding junctions. PDMS with a single ureidoguanosine unit at the end was synthesized by a postpolymerization strategy. PLA with a single 1,7-diamidonaphthyridine was synthesized by ring-opening polymerization from the appropriate functional initiator. Selective association of the end groups to form distinct, noncovalent connections between the respective homopolymers in blends was established by ^{1}H NMR spectroscopy. The orthogonal self-assembly of the resulting pseudoblock copolymer, driven by immiscibility between the polymer constituents was demonstrated.

Bulk polymer blends were prepared that have approximately symmetric composition and a 1:1 end-group stoichiometry. Small angle X-ray scattering combined with differential scanning calorimetry and transmission electron microscopy provide unambiguous evidence for the adoption of a lamellar morphology having long-range order, nanoscopic domain dimensions (20 nm pitch), and a sharp domain interface defined by the supramolecular building blocks.
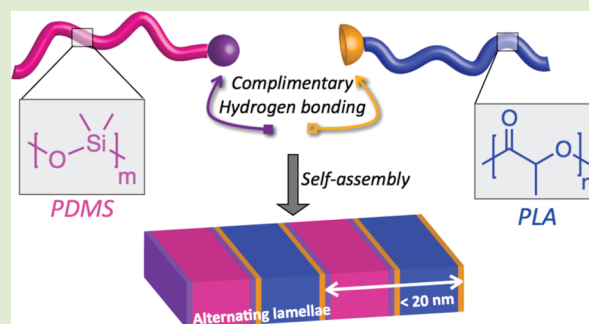
Performing hierarchical self-assembly by marrying supramolecular organization with block copolymer nanophase separation is an intriguing avenue for the design of complex, adaptive structures. Exploiting supramolecular interactions in soft matter has recently received significant attention as a strategy for bestowing materials with exceptionally dynamic behavior compared to covalent analogs.[1−6] A major advantage of this approach is that the interaction strength can be synthetically tuned by molecular design with systems involving two, three, or more complementary interactions.[7] This judicious balancing of the strength and reversibility of supramolecular interactions has been shown to lead to unique physical/mechanical properties in hybrid polymeric materials with implications in diverse arenas.[8,9]

Several design principles have been implemented to make self-organizing multicomponent polymer mixtures that exploit weak interactions to mimic morphologies adopted by conventional block polymers (Figure 1).[10−13] In these systems, association strength must be tailored to effectively simulate a covalent connection. For example, binary or ternary polymer blends with functional end-groups having multiple hydrogen bonding sites include those carrying complementary nucleobase derivatives,[14−18] ureidopyrimidinones (UPy) and 1,7-diamidonaphthyridines (Napy),[19−22] Hamilton receptors with barbiturates and triazines,[23−29] ureidoguanosine (UG) with Napy,[30−32]

and others can undergo phase separation on the nanometer size scale.[33]

Exemplary evidence for end-group association in solutions of multicomponent mixtures has been provided by ^{1}H NMR, infrared (IR), and ultraviolet−visible (UV−vis) spectroscopy. However, an unambiguous demonstration that bulk materials adopt well-defined nanostructures in accordance with the classical diblock copolymer phase diagram is less prevalent.[34] Typically, hydrogen bonding end-groups merely compatibilize mixtures of polymers that would otherwise be immiscible and undergo macrophase separation.[19,22] This generates distinct, albeit disorganized, nanoscopic domains enriched in either of the separate homopolymer segments.[33] There are rare cases in which telechelic homopolymers having self-complementary hydrogen bonding motifs at the chain ends organized into well-defined lamellae.[18,35] Alternatively, Matsushita and Noro demonstrated that well-ordered lamellae could be generated by blending multiply functional poly(ethylene imine) with various amounts of short-chain, carboxyl-terminal poly(dimethylsiloxane).[36]
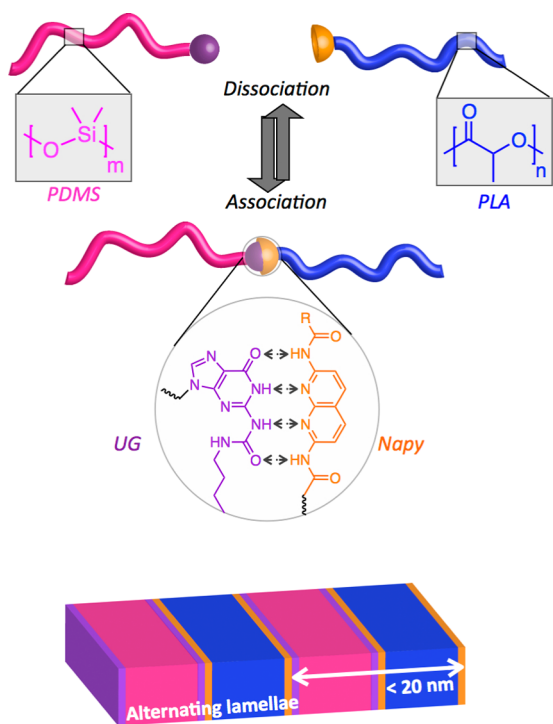
Figure 1. Illustration of reversible association between functional homopolymers to form supramolecular diblock copolymers with a noncovalently bound junction.

Here we describe a straightforward synthetic pathway to generate precisely functionalized homopolymers bearing end-groups capable of highly specific heterocomplementary 4-fold hydrogen bonding. Stoichiometric mixtures of functionalized poly(dimethylsiloxane) (PDMS) and poly(DL-lactide) (PLA) are shown to adopt organized lamellae with nanoscale domain periodicity as a consequence of the strong immiscibility between the components and the correspondingly low molar mass (Figure 1).

Design principles: The critical design feature to consider for these systems is the delicate balance between the thermodynamics that dictate the degree of immiscibility between the polymer components (i.e., the segregation strength) and the association strength of the interaction at the junctions (i.e., the

hydrogen bonding propensity) reflected by the equilibrium constant $K_a = [A \cdot B][A]^{-1}[B]^{-1}$ M^{-1}. Our previous work targeting small feature sizes with self-assembling diblock copolymers exploited the unusually strong immiscibility between poly(dimethylsiloxane) (PDMS) and poly(DL-lactide) (PLA).[37] Hillmyer and co-workers estimated a Flory−Huggins interaction parameter (χ) for this combination around unity.[38] Exceptionally small domains are therefore generated in thin-films of block copolymers having low degrees of polymerization ($N < 100$) and high compositional asymmetry (volume fraction, $f \approx 0.15$). Implementing this polymer combination in supramolecular block copolymers requires that strongly associating groups be incorporated to counteract macrophase separation. Additionally, the groups must be highly selective; self-association must be avoided to generate authentic diblock copolymer replicas. For example, the tendency of ureidopyr-imidinones to dimerize compromises the molecular makeup by essentially generating the corresponding homopolymer as contaminant. This heterogeneous composition may contribute to preventing well-organized morphologies from being readily adopted, as verified by microscopy and scattering.[17−20]

We chose to exploit the strong and selective 4-fold hydrogen bonding between UG and Napy derivatives.[39,40] This has been amply demonstrated in dilute solutions (toluene, CHCl₃). A self-dimerization equilibrium constant of $K_{dim} = 185$ M^{-1} was estimated for UG from ^{1}H NMR spectroscopy in CDCl₃.[41] In contrast, the value of K_a for the UG−Napy interaction was reported to be $\sim 10^7$ M^{-1}. We can roughly estimate that such a large K_a should more than compensate for the free energy of mixing of PDMS with PLA at moderate molar mass. For example, using $N = 150$ (for $M_n = 10$ kg mol^{-1}) and $\chi = 1$, the free energy can be estimated as $F \approx 20$ kJ mol^{-1} (corresponding to $K_a = 3 \times 10^3$ M). Attachment to polymer chains may adversely affect the strength and mobility. Indeed, the chemical nature of the backbone is critical; hydrophilic poly(ethylene oxide) oligomers notoriously impair supra-molecular polymerizations.[42]

Synthesis of functionalized polymers: Commercially available PDMS-OH, with a molar mass of 5 kg mol^{-1}, was used as starting material and initially functionalized with a ureidogua-nosine (UG) derivative through a mild hydroxyl−carboxylate esterification reaction catalyzed by 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDCI) and 4-

Scheme 1. Functionalization Strategies for Preparing PDMS-UG 1 and PLA-Napy 2
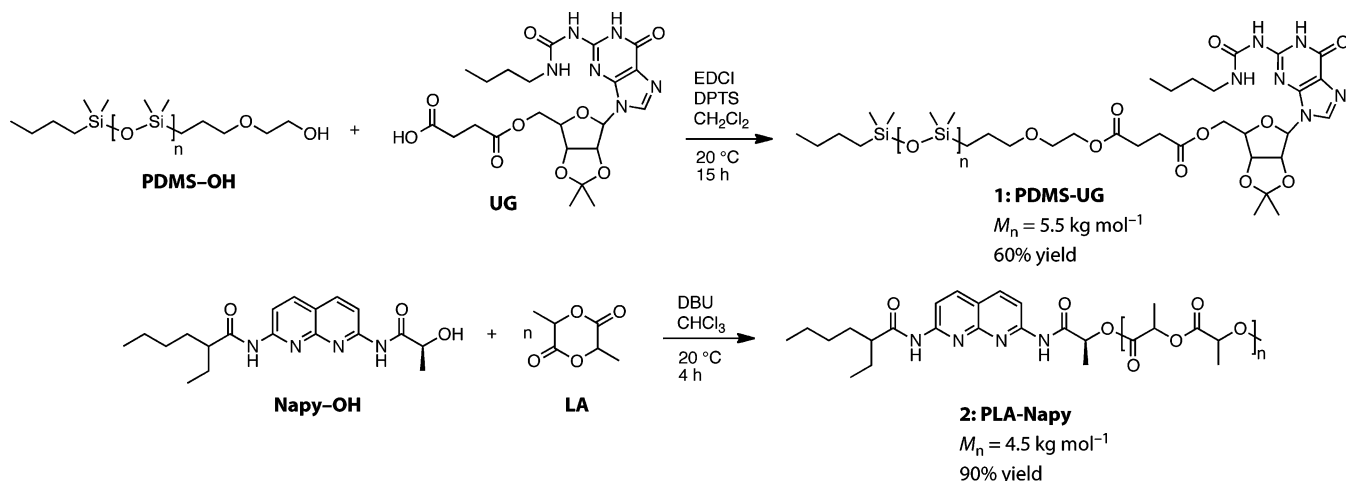
(dimethylamino)pyridinium *p*-toluenesulfonate (DPTS; Scheme 1a). Encountering difficulties with preparing the carboxylated UG derivative according to previous reports prompted us to seek an alternative synthetic route (see Supporting Information, Scheme S1) with the transesterification proceeding smoothly to afford PDMS-UG **1** in moderate yield (ca. 60%) after purification by column chromatography. This decreased yield may be attributed to fractionation during chromatography, which is consistent with the low molar mass dispersity ($Đ$ = 1.06, as measured in THF and compared with polystyrene standards; Figure S2). The average molar mass (M_n) of the starting material and product were confirmed by ^{1}H NMR spectroscopy, and most importantly, the spectrum of the product is consistent with high functionalization efficiency (Figure S1).

Functionalized poly(D,L-lactide) (PLA-Napy) **2** was prepared by initiating ring-opening polymerization (ROP) from the appropriate hydroxyl functional Napy-OH (Scheme 1b) resulting in excellent functionalization efficiency and higher yields compared with postpolymerization reactions.[19,43] Controlled polymerization of D,L-lactide (LA) was successful with the organocatalyst 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) and proceeded to high conversion with near quantitative introduction of the desired Napy end group (M_n = 4.8 kg mol^{-1} and $Đ$ = 1.07; Figures S3 and S4).[44]

End-group association: Supramolecular diblock copolymer **1·2** was prepared by dissolving the two functional homopolymers in a hydrophobic solvent that promoted heterodimerization. Deuterated chloroform was employed to facilitate NMR analysis directly prior to bulk block formation. The homopolymers were combined in a 1:1 stoichiometry with respect to end groups with hydrogen bonding initially being investigated in CDCl$_3$ (Figure 2). The resulting signals are
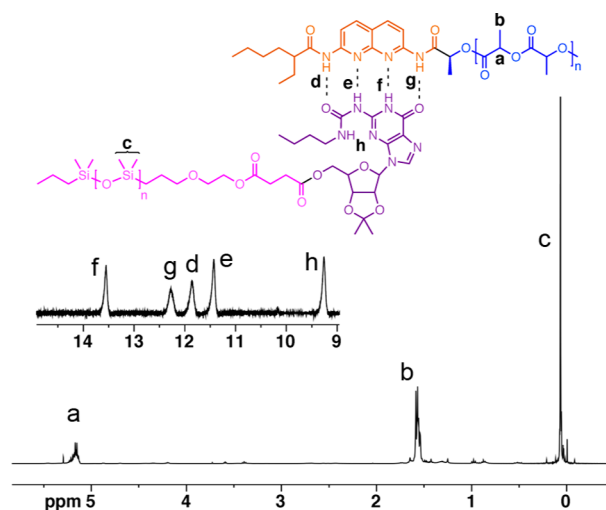

Figure 2. ^{1}H NMR spectra of equimolar mixture of functional PLA and PDMS homopolymers to form supramolecular block copolymer **1·2**. Inset shows the downfield signals associated with hydrogen-bonded protons.

consistent with strong association and corroborate signals observed for asymmetrically functional UG−Napy mixtures.[31,45] ^{1}H NMR spectra obtained with mixtures of small molecule derivatives of Napy and UG exhibit strong signals far downfield that are attributed to −N−H···O=C long-lifetime hydrogen bonding.[41] Polymer composition was confirmed by

integrating the respective signals and are consistent with the mass fractions in the originally prepared solid mixtures. The end-group selectivity does not appear to be compromised by the relatively large contribution of carbonyl groups from the PLA repeating units, which could act as competitive hydrogen bonding acceptors. No spectroscopic evidence was found for inhibition of end-group bonding fidelity.

Nanostructured supramolecular block copolymers: Having demonstrated strong association in solution, the solid-state behavior was then studied. Samples were prepared from a polymer solution (∼20 mg mL^{-1}) that correlates with an end-group concentration on the order of 10 mM. Under these conditions, the end groups are nearly quantitatively associated (Figure 2). The solvent was then allowed to evaporate slowly (∼24 h) at atmospheric pressure before drying further under vacuum at ambient temperature for 1 day. The quantity of polymer solution was such that the resulting polymer films are <0.5 mm thick. Both homopolymers are amorphous at ambient temperature, as corroborated by different scanning calorimetry (DSC; Figure 3). PDMS-UG is a clear, colorless, viscous liquid
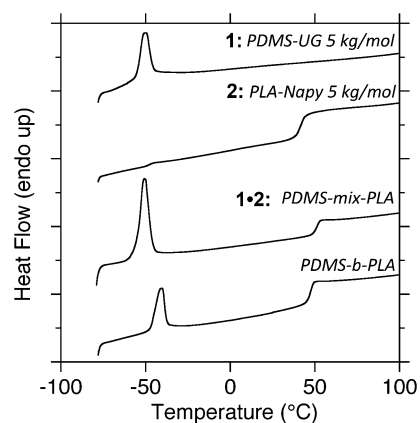

Figure 3. DSC thermograms for individual supramolecular building blocks (PDMS-UG 5 kg/mol and PLA-Napy 5 kg/mol), the mixture (PDMS-mix-PLA), and a conventional block copolymer (PDMS-*b*-PLA).

with a melting transition occurring near −50 °C. PLA-Napy is a white powder (or clear colorless film) with a glass transition temperature (T_g) near +45 °C. The resulting film of the polymer blend is also clear and colorless, suggesting the absence of macrophase separation. This contrasts with the PEO−PS and PI−PS systems, which resulted in "sticky flakes" upon drying.[31] Observance of the T_g associated with PLA being nearly identical in the blend and isolated homopolymer is consistent with microphase separation. Furthermore, the DSC thermogram measured for a covalent block copolymer (PDMS-*b*-PLA) with comparable characteristics that is known to order on the nanoscale suggests that macrophase separation was averted.

Small-angle X-ray scattering (SAXS) performed on films further demonstrate that nanoscale organization occurs. The presence of a strong principal scattering reflection at $q^* = 4\pi\lambda^{-1} \sin\theta$ provides evidence for the nanosized dimensions of adjacent domains comprised primarily of the respective homopolymers (according to average domain periodicity, $d^* = 2\pi q^{*-1}$; Figure 4).

The polymer blend **1·2** shows a scattering profile exhibiting remarkably sharp peaks with strong intensity and positions of
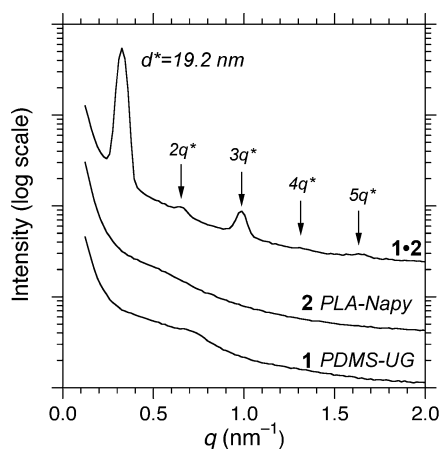
Figure 4. One-dimensional SAXS profiles for supramolecular block copolymer **1·2**.

Figure 5. TEM micrograph of supramolecular block copolymer **1·2**.

higher order diffraction peaks consistent with a lamellar morphology ($q/q^* = 1, 2, 3, 4, 5$). Diminished intensity of the $q/q^* = 2$ and 4 peaks is consistent with the coincidence of form factor extinction in lamellar samples with symmetric composition. This sample contains a stoichiometric ratio of end groups and a corresponding weight fraction of PLA equal to 0.46, owing to the nearly symmetric molar masses of the two components. Significantly, the position of the principal diffraction peak for **1·2** corresponds to an interlamellar domain spacing of 19.2 nm with the analogous conventional, covalently linked block copolymer exhibiting a lamellar morphology with a domain spacing on the order of 20 nm (Figure S5). This remarkable agreement between the conventional covalent block copolymer and its supramolecular analog suggests a high degree of functionality and nearly quantitative association of the hydrogen bonding units. Therefore, this likely allows the supramolecular junction points to form a distinct boundary at the domain interface, perhaps fortified by the intermolecular $\pi-\pi$ stacks between adjacent groups. We are keen to investigate the exact molecular makeup, molecular orientation, thickness and extent of intermixing of the segments comprising the domain boundary. Our hypothesis is that the relatively bulky end groups act to reinforce the domain boundary such that intermixing is substantially retarded and the consequentially increased energetic penalty for mixing manifests itself in exceptionally sharp boundaries and, hence, narrow diffraction peaks. The extent of broadening of the lamellar interfaces is thus not strictly a function of the interaction strength as reflected in the Flory–Huggins interaction parameter χ. The selectivity exhibited by the UG–Napy hydrogen-bonded heterodimers is critical to the organization observed in this system. Indeed, when analogous UPy functionalized PDMS is mixed with PLA-Napy, the lamellar morphology is not adopted (see Supporting Information, Figure S6).

Visualization of the lamellar morphology for thin films of the supramolecular diblock copolymer, **1·2**, prepared by drop-casting onto copper grids could be achieved by TEM. The natural contrast between domains rich in PDMS and PLA is apparent in transmission electron micrographs (Figure 5) with the lamellar periodicity ranging from 13−17 nm. The darker layers also appear thicker than the lighter layers. Both of these observations could be manifestations of the morphology orientation. Alternating lamellae that are not perfectly oriented normal to the focal plane will cause the dark domains to appear
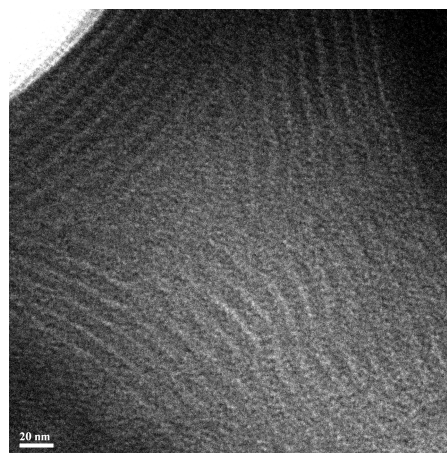
artificially large with a concomitant artificial decrease in periodicity. As alignment and annealing strategies were not employed, the isotropic arrangement of lamellae is expected. Nevertheless, the micrograph is consistent with the bulk morphology and domain spacing determined from small-angle X-ray scattering.

In conclusion, these studies have shown that the formation of well-organized morphologies is a consequence of the delicate interplay between polymer component interactions (i.e., χ) and can be used to prepare nanoscale patterns in thin films. Significantly, similar supramolecular block copolymers prepared using poly(ethylene oxide) proved difficult to enhance order because of the necessity of high humidity annealing conditions.[31] Not only does this demonstrate a strong and detrimental influence on hydrogen bonding capabilities for PEO-based systems, but it clearly shows the influence of polymer backbone for these supramolecular systems.[42] To develop robust design rules, we are avidly exploring the relationship between end-group stoichiometry, composition, and morphology in this system with a view to establishing the extended phase space needed to effectively prepare a wide variety of well-defined morphologies. An additional benefit of this strategy is that removal of one phase does not entail cleavage of a covalent bond allowing for the fabrication of nanoporous materials and masks for lithography by simple washing with a selective solvent. This presents a substantial advantage and convenient alternative to chemical etching techniques.[46−49]

■ ASSOCIATED CONTENT

ⓢ Supporting Information

Experimental and synthetic details, SEC chromatograms, and ^{1}H NMR spectra. 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.

■ ACKNOWLEDGMENTS

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