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Polymerization-induced self-assembly enables access to diverse highly ordered structures through kinetic and thermodynamic pathways†

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Polymerization-induced self-assembly (PISA) has emerged as a powerful technique for generating microphase-separated structures, but research has primarily focused on systems exhibiting “disordered” structures. Here, we demonstrate the facile construction of various highly ordered microphase-separated structures *via* PISA, with and without kinetic control through manipulation of the glass transition temperature (T_g) of the core-forming blocks. We synthesized diblock copolymers in an ionic liquid (40 wt% solute) by polymerizing styrene or 2-hydroxyethyl acrylate from one end of poly(ethylene glycol). When using polystyrene as the core-forming block, its high T_g relative to the polymerization temperature resulted in the formation of kinetically trapped structures, including pure hexagonal close-packed (HCP) spheres exhibiting X-ray diffraction peaks up to the 17th-order. Conversely, lower- T_g core-forming block [poly(2-hydroxyethyl acrylate)] led to thermodynamically stable, highly ordered structures, including a double-gyroid morphology. These results highlight the efficacy of PISA for generating diverse, highly ordered microphase-separated structures from simple diblock copolymers and demonstrate its potential to access structures unattainable through conventional *ex situ* polymerization.

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Introduction

Self-assembly and microphase separation are fundamental processes with significant implications across diverse fields. These intricate processes often yield kinetically controlled structures, highlighting their importance in producing unique and functional architectures.^{1–3} In this context, polymerization-induced self-assembly (PISA) has garnered considerable interest due to its ability to efficiently prepare micelles and vesicles of controlled structure and size. During PISA, polymerization and self-assembly proceed concurrently; the kinetics of both processes interactively influence the resulting structures.^{3–13}

When *in situ* polymerization of copolymers is conducted in concentrated solution or bulk, microphase separation occurs. This phenomenon, pioneered by the group of Hillmyer,^{14–16} is termed polymerization-induced microphase separation (PIMS),

a subset of PISA. PIMS has garnered increasing attention as a facile route to microphase-separated (nanoporous) structures and for its potential applications in electroconductive materials, gas adsorbents, and membranes.^{17–27} Hereinafter, we will use ‘PISA’ to include ‘PIMS’.

However, most PISA studies have focused on disordered microphase separation, characterized by broad diffraction peaks in small-angle X-ray scattering (SAXS) profiles. In contrast, microphase separation prepared through conventional *ex situ* polymerization or solution casting methods is well-established to exhibit various long-range ordered structures, such as lamellae (LAM), hexagonally packed cylinders (HEX), face-centered cubic (FCC), and body-centered cubic (BCC).^{18,28,29} As a notable exception, the group of Armes³⁰ reported long-range ordered microphase-separation with sharp SAXS diffraction peaks *via* PISA synthesis of hydrogenated polybutadiene and benzyl methacrylate (BzMA) monomer in *n*-dodecane. Their work focused on a BCC-to-HEX transition process, rather than a broader exploration of ordered structures.

Despite these advancements, creating highly ordered microphase-separated structures through PISA remains challenging, which is crucial for their use as electroconductive and gaseous adsorptive materials. In particular, not all structures observed in *ex situ*-prepared diblock copolymers have been replicated using PISA; for example, double-gyroid (GYR) structures have not yet been reported *via* PISA. Moreover, PISA processes in dilute or semidilute solutions can become

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kinetically trapped, leading to unusual behaviors of micelles/vesicles.^{3,31–36} Similarly, PISA syntheses in concentrated solution or bulk conducted kinetically controlled conditions are expected to yield microphase-separated structures that are inaccessible through *ex situ* polymerization.

In this study, we have comprehensively explored PISA synthesis in concentrated solutions with various degrees of polymerization for the core-forming blocks to prepare well-defined, ordered microphase-separated structures. We examined two types of core-forming blocks with glass transition temperatures (T_g) both above and below the polymerization temperature. Specifically, styrene or 2-hydroxyethyl acrylate (HEA) was polymerized from one end of poly(ethylene glycol) [PEG; macromolecular chain-transfer agent (macro-CTA)] *via* reversible addition–fragmentation chain-transfer (RAFT) polymerization at 60 °C in an ionic liquid, 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIM][PF₆]) (Scheme 1). While styrene and HEA are soluble in [BMIM][PF₆], their corresponding polymers are insoluble, causing the resulting block copolymers (PEG₄₅–PS_{*n*} or PEG₄₅–PHEA_{*n*}) to self-assemble and undergo microphase separation as polymerization progresses. Polystyrene (PS) is known to have T_g of approximately 100 °C,³⁷ while T_g of poly(2-hydroxyethyl acrylate) (PHEA) is around 15 °C.^{38,39} Hence, the self-assembled PS blocks become glassy, whereas the PHEA blocks remain rubbery. The glassy core domains may become kinetically trapped, potentially preventing structural transformation. Consequently, we demonstrate that PISA synthesis can generate a range of highly ordered microphase-separated structures, influenced by the T_g

of the core-forming block. Furthermore, we show that kinetically controlled PISA can lead to unusual structures not observed in conventional microphase separation of diblock copolymers.

Results and discussion

PISA synthesis

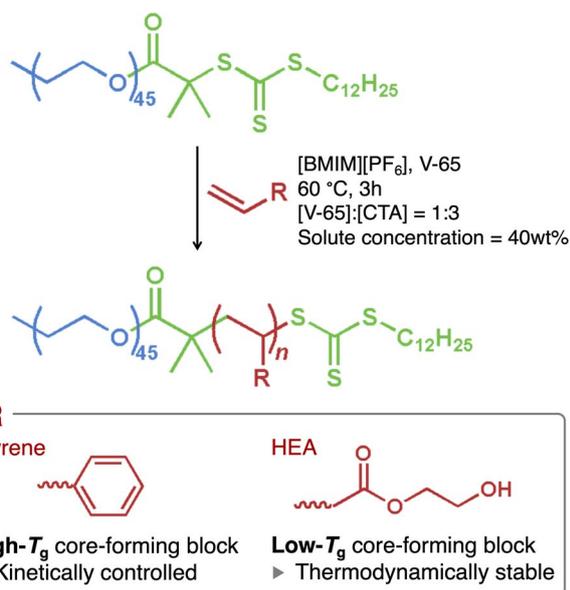
The macro-CTA was synthesized *via* Steglich esterification of hydroxy-terminated PEG with a carboxylic acid-functionalized CTA (Scheme S1†). Complete functionalization of PEG by CTA was confirmed by ¹H nuclear magnetic resonance (NMR) spectroscopy and UV spectroscopy (Fig. S1 and S2†). The RAFT polymerization (Scheme 1) exhibited good control, as indicated by the monomer conversions exceeding 92% and the dispersity (D) below 1.22 for all samples prepared in this study (Fig. S3, S4, 1a, b, and Table S1†). D is defined as M_w/M_n , where M_w and M_n denote the weight- and number-average molecular weights.

The T_g values of the PS and PHEA blocks, in the presence of [BMIM][PF₆], were investigated by differential scanning calorimetry (DSC) (Fig. 1c and d). The results confirm T_g of approximately 102 °C for PS (the exothermic shift after the glass transition may be caused by the relaxation of internal stress). In contrast, T_g of PEG₄₅–PHEA₁₃₆ was –13 °C, and no distinct T_g signal was observed for lower n samples of PEG₄₅–PHEA_{*n*}, despite the reported T_g value of bulk PHEA being around 15 °C.^{38,39} Additionally, PEG₄₅–PHEA₁₃₆ was prepared in ethyl acetate (without [BMIM][PF₆]), followed by evaporation of the ethyl acetate and DSC analysis. This samples exhibited slightly higher T_g (–10 °C). These data indicate that PS domains are almost solvent-free and exist in a glassy state at the polymerization temperature, whereas PHEA domains likely contain solvent molecules and are in a rubbery state.

Ordered spheres with and without kinetic control

Regarding the microphase-separated structures, it is remarkable that the SAXS profiles for these samples exhibited sharp, high-order diffraction peaks (Fig. 2). PEG₄₅–PS₂₃ displayed diffraction peaks whose positions align with a BCC lattice (the ratio to the first-order peak was 1, $\sqrt{2}$, $\sqrt{3}$, $\sqrt{4}$,...). This indicates that the PS block formed spherical core domains arranged on a BCC lattice. The domain spacing (center-to-center distance) between the nearest-neighbor spheres was $\sqrt{(3/2)2\pi/q^*} = 13.6$ nm, where q^* stands for the q value of the primary peak. BCC structures are commonly observed in the microphase separation of diblock copolymer solutions prepared by *ex situ* polymerization when the core-forming blocks are short.

Intriguingly, more than 10 peaks were observed in PEG₄₅–PS₄₅, all of which matched the allowed reflections from a hexagonal close-packed (HCP) structure with a nearest-neighbor domain spacing of $\sqrt{(4/3)2\pi/q^*} = 19.0$ nm (Fig. 2a–c). While the (013), (020), and (014) reflections were not detected, likely due to the form factor of spherical PS domains, a 17th-order peak (122) was observed, despite the use of non-microbeam SAXS (with an X-ray spot size of 0.2 mm in



Scheme 1 PISA synthesis used in this study: RAFT polymerization to synthesize PEG₄₅–PS_{*n*} (high T_g core-forming block) and PEG₄₅–PHEA_{*n*} (low T_g core-forming block), where the subscripts indicate the target number-average degree of polymerization. V-65 (2,2′-azobis(2,4-dimethylvaleronitrile)) is an azo-type initiator with a 10-hours half-life temperature of 51 °C.



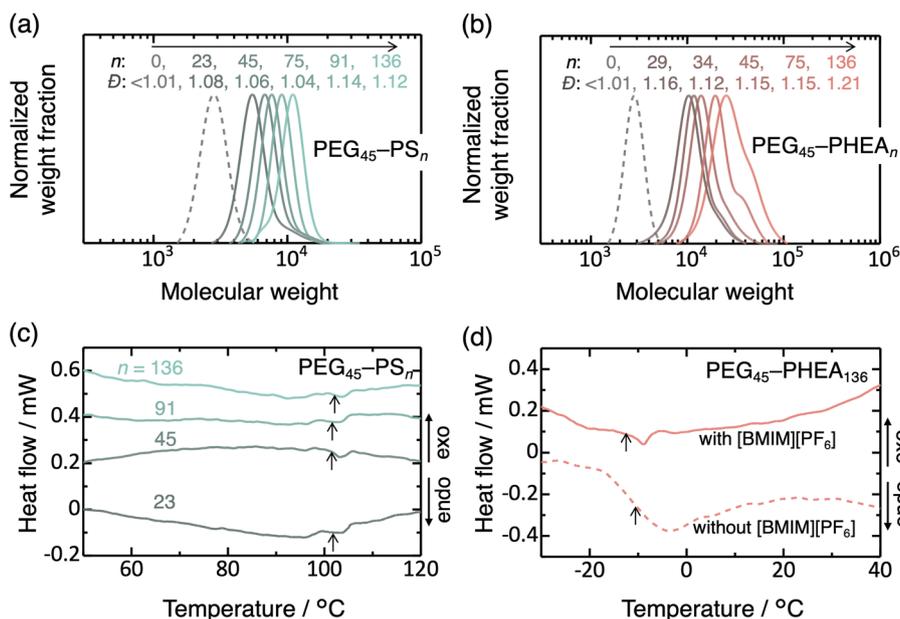


Fig. 1 SEC traces (a and b) and DSC thermograms (c and d) of PEG₄₅-PS_n (a and c) and PEG-PHEA_n (b and d). DSC was performed with the non-volatile solvent [BMIM][PF₆] present, at the polymer concentration of 40 wt%, except for the dotted curve in panel (d). Arrows in panels (c) and (d) indicate T_g . In panels (a) and (b), "molecular weight" represents the relative molecular weight obtained with poly(methyl methacrylate) standards.

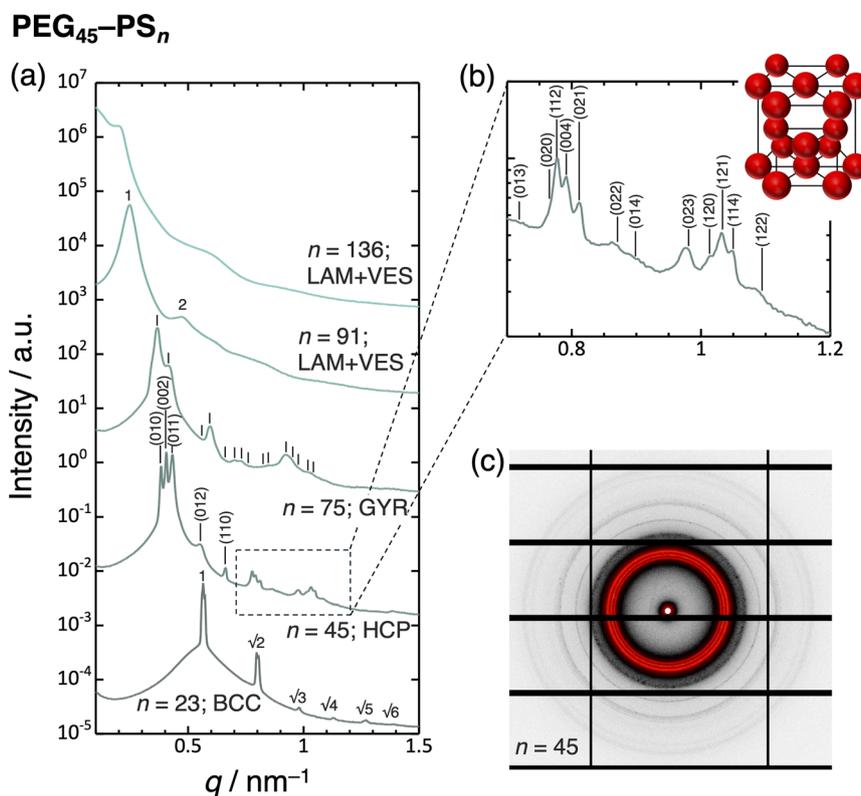


Fig. 2 (a) SAXS profiles for PEG₄₅-PS_n in [BMIM][PF₆] with varied degrees of polymerization of PS at 25 °C, prepared by PISA at the solute concentration of 40 wt%. Short vertical lines for $n = 75$ indicate the allowed reflections of GYR. (b) Close-up of the SAXS profile of PEG₄₅-PS₄₅ and schematic illustration of HCP structure. Allowed reflections for HCP ($n = 45$) correspond to the following ratio of the peak positions: $\sqrt{32}$, $\sqrt{36}$, $\sqrt{41}$, $\sqrt{68}$, $\sqrt{96}$, $\sqrt{113}$, $\sqrt{128}$, $\sqrt{132}$, $\sqrt{137}$, $\sqrt{144}$, $\sqrt{164}$, $\sqrt{176}$, $\sqrt{209}$, $\sqrt{224}$, $\sqrt{233}$, $\sqrt{240}$, and $\sqrt{260}$. (c) Two-dimensional SAXS pattern of PEG₄₅-PS₄₅.



halo in its SAXS profile, with a domain spacing of $2\pi/q^* = 12.2$ nm (Fig. 3a). This disordered structure is attributed to the weaker segregation of PEG₄₅-PHEA_n compared to PEG₄₅-PS_n. The SAXS profiles of PEG₄₅-PHEA₃₄ and PEG₄₅-PHEA₄₅ exhibited diffraction peaks at positions corresponding to HEX structures (with ratios of 1, $\sqrt{3}$, $\sqrt{4}$, $\sqrt{7}$, $\sqrt{9}$, and $\sqrt{11}$). The domain spacing of the nearest-neighbor cylinders ($\sqrt{(4/3)} 2\pi/q^*$) was 15.4 nm for PEG₄₅-PHEA₃₄ and 16.8 nm for PEG₄₅-PHEA₄₅. The 16.8 nm spacing observed for PEG₄₅-PHEA₄₅ (HEX) is smaller than that the 19.0 nm spacing for PEG₄₅-PS₄₅ (HCP). The dimensional relationship is consistent with previous observations, suggesting that the kinetically trapped HCP structure cannot readily transform into HEX.^{30,53} These results indicate that the formation of the pure HCP structure in PISA of PEG₄₅-PS₄₅ can be attributed to the higher T_g of the PS block, which more effectively hinders the rearrangement of spherical core domains and prevents morphological transformation to cylinders.

Highly ordered gyroid structure

A notable finding within PEG₄₅-PHEA_n series is the formation of a well-defined double-gyroid (GYR) structure in PEG₄₅-PHEA₇₅. GYR formation was confirmed by the intensity of the primary peak being approximately 10 times higher than that of the secondary peak, with the peak positions accurately matching the allowed reflections of GYR (Fig. 3). Of particular interest,

a 16th-order peak was observed, despite the invisibility of the (431), (440), and (541) reflections. A GYR structure was also observed in PEG₄₅-PS₇₅, although the diffraction peaks were less distinct (Fig. 2) than those of PEG₄₅-PHEA₇₅. $\sqrt{6} \times 2\pi/q^* = 50.5$ nm. The lattice parameters were for PEG₄₅-PHEA₇₅ and 41.7 nm for PEG₄₅-PS₇₅. The smaller lattice parameter observed in PEG₄₅-PS₇₅ may be attributed to the glassy nature of the PS domains, which could hinder the expansion of the GYR structure during the PISA process. GYR is a known thermodynamically stable structure in the microphase separation of block copolymers, but it typically exists within a narrow compositional window (or is sometimes absent) for linear diblock copolymers.^{29,54-56} To the best of our knowledge, such high-order diffraction peaks for a GYR structure have not been previously reported for diblock copolymers prepared *via ex situ* polymerization. Additionally, this is the first observation of GYR structures through PISA. These results suggest that PISA, with optimized core-forming and stabilizing block length, is an effective method for preparing well-defined GYR structures, and that low- T_g core-forming blocks may be particularly suitable for their formation.

Kinetically controlled competition between lamella and vesicle

Another unexpected observation is the broadening of diffraction peaks as the degree of polymerization of the PS block

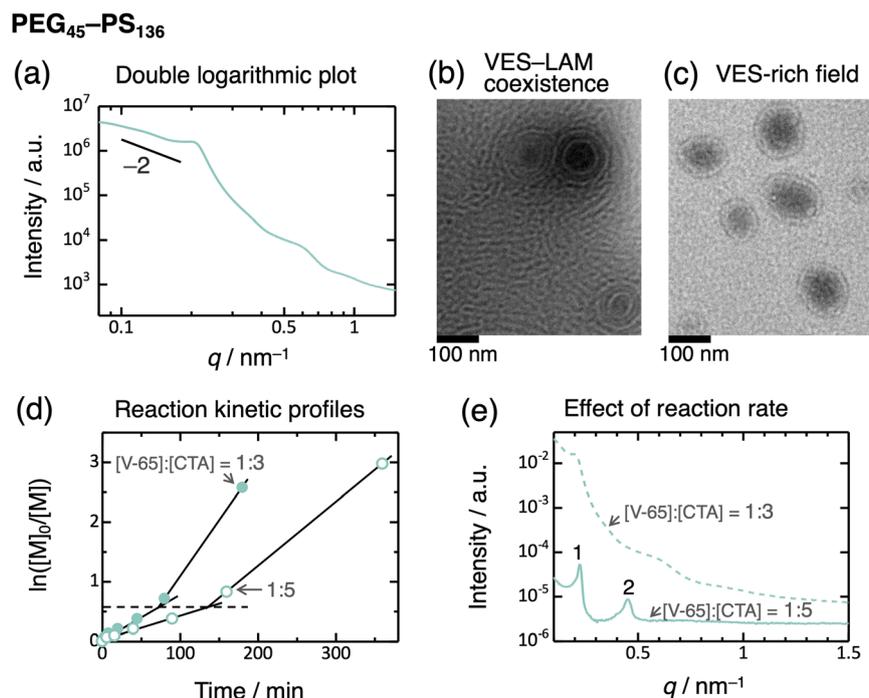


Fig. 4 (a) Double logarithmic plot of the SAXS profile for PEG₄₅-PS₁₃₆ in [BMIM][PF₆] (the same data as in Fig. 2a). (b and c) TEM images of PEG₄₅-PS₁₃₆ in [BMIM][PF₆]. Panels (b and c) show different fields of view of the same sample; panel b displays vesicle–lamella coexistence, and panel (c) shows a vesicle-rich field. (d) Reaction kinetic profiles with [V-65] : [CTA] ratios of 1 : 5 (unfilled circle) and 1 : 3 (filled circle) at 60 °C. The broken line represents the $\ln([M]_0/[M])$ value at the inflection points. (e) Effect of the reaction rate on the SAXS profiles of PEG₄₅-PS₁₃₆ in [BMIM][PF₆] at 25 °C. The PISA synthesis was performed at 60 °C for 6 hours with a [V-65] : [CTA] ratio of 1 : 5 (solid curve) and for 3 hours with a [V-65] : [CTA] ratio of 1 : 3 (broken curve; same data as in Fig. 2a).



exceeds 75. PEG₄₅-PS₉₁ exhibited broad peaks with positions of a 1 : 2 ratio (Fig. 2a), and the volume fraction of the PS domain is adequately high. This observation indicates lamella formation, but the structure is not well-defined. Moreover, PEG₄₅-PS₁₃₆ exhibited much broader peaks, without higher-order peaks beyond the second order, indicating a disordered structure. In contrast, PEG₄₅-PHEA₁₃₆ exhibited relatively distinct peaks consistent with a lamella structure (Fig. 3). This transition behavior of PEG-PHEA (BCC → HEX → GYR → LAM) is similar to that observed in conventional *ex situ*-prepared block copolymers. To further consider the disordered structure of PEG₄₅-PS₁₃₆, we saw the SAXS profile as a double-logarithmic plot, which shows that the scattering intensity is close to the scaling relationship of “intensity $\sim q^{-2}$ ” at the low- q region⁵⁷ (Fig. 4a). This scaling suggests the presence of vesicles. To confirm the vesicle formation in PEG₄₅-PS₁₃₆, we performed transmission electron microscopy (TEM). Consequently, vesicles (VES) with the coexistence of LAM were observed (Fig. 4b and c). We note that the solvent, [BMIM][PF₆], is non-volatile and electron-rich, and thus, the dark-colored inside of the vesicles implies that the vesicles contain [BMIM][PF₆]. The broad SAXS peaks can therefore be attributed to the presence of vesicles, as the periodic structure becomes disordered. The domain spacing of the lamella determined by SAXS was $2\pi/q^* = 27.1$ nm, which agrees well with the TEM result of 25 ± 6 nm.

Vesicles typically grow through fusion and/or molecular exchange, and sedimentation of these enlarged vesicles results in LAM formation. This process reduces the bilayer curvature and minimizes the bending energy.^{58–62} However, if the growth mechanisms are inhibited, the vesicle structure may become trapped. In a dilute solution, the low collision probability allows vesicles to remain metastable for extended periods. In contrast, LAM is typically observed in more concentrated solutions rather than VES,²⁹ as the higher collision probability should lead to LAM formation. In this study, the glassy PS core domains of VES hinder both fusion and molecular exchange. As a result, the VES structure becomes kinetically trapped in spite of the high solute concentration (40 wt%).

To validate this hypothesis, we performed PISA synthesis at a reduced reaction rate of the polymerization by decreasing the molar ratio of initiator (V-65) to CTA ([V-65] : [CTA]) to 1 : 5.⁶³ As expected, the reaction rate decreased, as evidenced by the shallower slope in the plot of $\ln[M]_0/[M]$ versus time (Fig. 4d), where $[M]$ stands for the molar concentration of monomer, and $[M]_0$ is the initial $[M]$ value. An inflection point, indicative of acceleration of reaction rate, was observed in this plot. This phenomenon is often seen during PISA syntheses and is attributed to the onset of self-assembly¹¹ (monomer encapsulation within the micelle core, leading to an increased local monomer concentration). In this study, the inflection occurred at the same $\ln[M]_0/[M]$ values (*i.e.*, similar conversions) for both [V-65] : [CTA] ratios. That is, the self-assembly initiates at a degree of polymerization independent of reaction rates investigated. Nonetheless, the SAXS profile of the PEG₄₅-PS₁₃₆ prepared using the lower initiator concentration exhibited relatively sharp diffraction peaks (up to the second order) of a LAM structure (Fig. 4e). This suggests that rapid

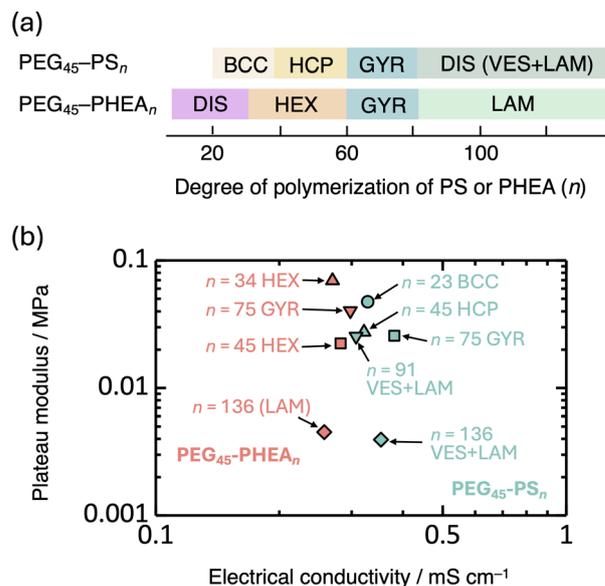


Fig. 5 (a) Quasi-phase diagram of PEG₄₅-PS_n (high- T_g core-forming block) and PEG₄₅-PHEA_n (low- T_g core-forming block) prepared via PISA in [BMIM][PF₆] in 40 wt% solute. (b) Plateau modulus obtained from oscillatory rheometry plotted against electrical conductivity for PEG₄₅-PS_n (turquoise symbols) and PEG₄₅-PHEA_n (pink symbols) in [BMIM][PF₆] with 40 wt% solute at 25 °C.

polymerization of the high- T_g core-forming block during PISA leads to rapid vitrification of the membrane, trapping the VES structure and preventing its transformation to LAM. Conversely, slow polymerization allows the growth of VES and the transformation to LAM before becoming glassy. In other words, the ordered/disordered states can be controlled by the reaction rate.

On the other hand, the low T_g of the PHEA blocks facilitates fusion and molecular exchange, leading to LAM formation with far fewer coexisting vesicles, as indicated by the sharper diffraction peaks, despite the lack of the TEM images due to the unfortunately poor contrast between the PEG and PHEA blocks in the presence of [BMIM][PF₆]. This result is consistent with the competition between VES and LAM as discussed above.

Relationship between structure and viscoelastic/electrical properties

The observed structures are summarized in Fig. 5a as a quasi-phase diagram. We conducted oscillatory rheometry and impedance spectroscopy to characterize these structures (Fig. S6–S9†). The plateau moduli, determined from the storage modulus at the minimum of the loss tangent, varied by more than an order of magnitude depending on the structure; the ordered structures tended to exhibit higher plateau moduli than the disordered structures (Fig. 5b and Table S1†). In contrast, the electrical conductivity remained relatively constant across the different structures due to the high ionic liquid content (60 wt%) and was primarily influenced by the choice of core-forming block (PS or PHEA). Thus, structural control can enhance the modulus while maintaining the conductivity.



Conclusions

We explored ordered structures through PISA during the syntheses of diblock copolymers with various degrees of polymerization and two distinct core-forming blocks with differing T_g . With the high- T_g core-forming blocks (PEG₄₅-PS_{*n*}), we observed structural transitions of BCC → HCP → GYR → DIS (VES + LAM) as the degree of polymerization of the PS block increased (Fig. 5a). Notably, a highly ordered, pure HCP structure was observed. The formation of the HCP structure is unusual in conventional diblock copolymers prepared *via ex situ* polymerization and is attributed to kinetic effects inherent to the PISA process. Similarly, the presence of the VES structure is also likely kinetically driven, as the competition between the VES (disordered) and LAM (ordered) states is influenced by the polymerization rate. In contrast, the low- T_g system (PEG₄₅-PHEA_{*n*}) did not exhibit HCP and VES + LAM structures. Instead, DIS → HEX → GYR → LAM transitions were observed with increasing the PHEA block length (Fig. 5a). This transition behavior qualitatively aligns with conventional microphase separation observed in *ex situ*-synthesized diblock copolymers, although ordered spherical phases were not formed due to the weak segregation of PEG₄₅-PHEA_{*n*}. However, we found a highly ordered GYR structure compared to previously reported GYR structures of *ex situ*-synthesized diblock copolymers.

Moreover, the plateau modulus was tunable by more than one order of magnitude through structural variation while maintaining electrical conductivity. While the absence of core-crosslinking in this study limits the achievable moduli compared to chemically crosslinked solid polymer electrolytes,^{18,22,23} these structure–property relationships are crucial for future design of high-modulus solid polymer electrolytes by combining precise structural control with crosslinking strategies. Additionally, despite the electrical conductivity being independent of the structure due to the high ionic liquid content (60 wt%), the gyroid (GYR) structure is known to enhance ion transport.^{56,64} Thus, insights into the fabrication of well-defined GYR structures are valuable for the applications. Therefore, PISA synthesis provides a facile route to a wide range of highly ordered microphase-separated structures from simple, conventional diblock copolymers, offering significant potential for applications. Furthermore, the kinetic effect afforded by the PISA process with high- T_g core-forming blocks enables the formation of structures inaccessible through conventional *ex situ* polymerization.

Data availability

The data are available from the authors upon reasonable request.

Author contributions

I. S.: data curation, formal analysis, investigation, validation, writing – review & editing. A. S.-N.: resources, supervision, writing – review & editing. R. T.: conceptualization, data curation, formal analysis, funding acquisition, methodology, project

administration, resources, supervision, validation, visualization, writing – original draft.

Conflicts of interest

There are no conflicts to declare.

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