Chinese Journal of Polymer Science Vol. 31, No. 1, (2013), 71–82

Chinese Journal of Polymer Science

ANIONIC SYNTHESIS OF A "CLICKABLE" MIDDLE-CHAIN AZIDE-FUNCTIONALIZED POLYSTYRENE AND ITS APPLICATION IN SHAPE AMPHIPHILES

Kan Yue[a], Jinlin He[a, b], Chang Liu[a], Mingjun Huang[a], Xue-Hui Dong[a], Kai Guo[a], Peihong Ni[b], Chrys Wesdemiotis[a, c], Roderic P. Quirk[a], Stephen Z. D. Cheng[a*] and Wen-Bin Zhang[a*]

[a] *Department of Polymer Science, College of Polymer Science and Polymer Engineering, The University of Akron, Akron, Ohio 44325-3909, USA*

[b] *College of Chemistry, Chemical Engineering, and Materials Science, Jiangsu Key Laboratory of Advanced Functional Polymer Design and Application, Soochow University, Suzhou 215123, China*

[c] *Department of Chemistry, The University of Akron, Akron, Ohio 44325-3601, USA*

Abstract "Click chemistry" is, by definition, a general functionalization methodology (GFM) and its marriage with living anionic polymerization is particularly powerful in precise macromolecular synthesis. This paper reports the synthesis of a "clickable" middle-chain azide-functionalized polystyrene (mPS-N_3) by anionic polymerization and its application in the preparation of novel shape amphiphiles based on polyhedral oligomeric silsesquioxane (POSS). The mPS-N_3 was synthesized by coupling living poly(styryl)lithium chains (PSLi) with 3-chloropropylmethyldichlorosilane and subsequent nucleophilic substitution of the chloro group in the presence of sodium azide. Excess PSLi was end-capped with ethylene oxide to facilitate its removal by flash chromatography. The mPS-N_3 was then derived into a giant lipid-like shape amphiphile in two steps following a sequential "click" strategy. The copper(I)-catalyzed azide-alkyne cycloaddition between mPS-N_3 and alkyne-functionalized vinyl-substituted POSS derivative (VPOSS-alkyne) ensured quantitative ligation to give polystyrene with VPOSS tethered at the middle of the chain (mPS-VPOSS). The thiol-ene reaction with 1-thioglycerol transforms the vinyl groups on the POSS periphery to hydroxyls, resulting in an amphiphilic shape amphiphile, mPS-DPOSS. This synthetic approach is highly efficient and modular. It demonstrates the "click" philosophy of facile complex molecule construction from a library of simple building blocks and also suggests that mPS-N_3 can be used as a versatile "clickable" motif in polymer science for the precise synthesis of complex macromolecules.

Keywords: Living anionic polymerization; Polyhedral oligomeric silsesquioxane (POSS); "Click" chemistry; General functionalization methodology (GFM).

INTRODUCTION

In spite of its long history, living anionic polymerization, particularly alkyllithium-initiated polymerization of styrenic and dienic monomers, remains one of the best methods to prepare polymers with precise control over the major molecular parameters including molecular weight, polydispersity and polymer architecture[1–5]. One of its unique features is the one-pot living functionalization or block copolymerization owing to the living nature of the polymeric organolithium species[1–4]. However, the scope of living functionalization is also profoundly limited by the low functional group tolerance of organolithium species. With a few exceptions[4, 6–9], many of these chain-end functionalization reactions are not quantitative and protection/deprotection strategies are usually

* Corresponding authors: Stephen Z. D. Cheng, E-mail: scheng@uakron.edu
Wen-Bin Zhang, E-mail: wz8@uakron.edu

Invited lecture presented at the International Symposium on Polymer Physics, 2012, Chengdu, China
Received September 25, 2012; Revised October 8, 2012; Accepted October 10, 2012
doi: 10.1007/s10118-013-1215-x

required[1, 4]. It is thus very desirable to develop general functionalization methodologies (GFM) in combination with living anionic polymerization for precision macromolecular synthesis[1, 8, 10–12].

Recently, two GFMs have been reported based on (1) the addition of polymeric anions to substituted 1,1-diphenylethylene derivatives[1, 4] and (2) the hydrosilylation reaction[8, 10–13], respectively. While the former is advantageous in quantitative functionalization affording a living functionalized species for further modification, the latter benefits from the compatibility of silyl-hydride group with living anionic polymerization conditions, the stability of Si—H functionalized polymer in air for long term storage, and the versatility of further derivation with diverse commercially available alkenes. Based on these methodologies, both chain-end[8, 14–17] and in-chain[13] functionalized polymers have been successfully synthesized, and further chemical modifications have been demonstrated. Yet, both methods are still not "perfectly" general since the former often requires protection/deprotection schemes and the efficiency of hydrosilylation in the latter approach is not always satisfactory.

The advent of the "click" chemistry concept opens enormous new opportunities for GFM[18–20]. "Click" chemistry refers to those highly efficient chemical transformations that proceed under mild conditions regio-selectively and quantitatively with minimum efforts for purification[18, 19]. So far, two reactions have been recognized to possess most features of a typical "click" reaction. They are the copper-catalyzed azide-alkyne [3+2] cycloaddition (CuAAC) reaction[18, 21] and the thiol-ene reaction[22–24]. The extremely high efficiency and functional group tolerance make these reactions quite suitable as a GFM to prepare functional polymers. While the idea has been demonstrated extensively in combination with controlled radical polymerization[19, 25], the introduction of "clickable" functionalities, such as azide[26, 27], alkyne[26, 28, 29], and alkene[12, 30, 31], into polymers prepared by anionic polymerization, is only recent. Nevertheless, the marriage of "click" chemistry and living anionic polymerization promises a powerful approach in creating complex macromolecules with molecular precision[19].

Herein, we report the design and synthesis of a "clickable" middle-chain azide-functionalized PS (mPS-N_3) and its application as a building block in the construction of novel shape amphiphiles. The middle-chain azide group on PS is introduced *via* the coupling reaction between poly(styryl)lithium and 3-chloropropylmethyldichlorosilane, followed by the nucleophilic substitution with sodium azide. The mPS-N_3 can be used as a general building block in polymer synthesis. As an example, a shape amphiphile[14, 15, 32, 33] resembling "giant lipids"[16, 17, 34, 35], *i.e*. a polar polyhedral oligomeric silsesquioxane (POSS)[36, 37] head tethered with two identical polymer tails as a hybrid polymer[38–40], is synthesized in two steps from mPS-N_3 following a sequential "click" approach[41, 42].

EXPERIMENTAL

Chemicals and Solvents

sec-Butyllithium (FMC Lithium, 12 wt% in cyclohexane) was used after double titration with allyl bromide[42]. Benzene (EMD, ACS grade), ethylene oxide (99.5+%, Aldrich) and styrene (99%, Aldrich) were purified as reported previously for anionic polymerizations[11, 43]. 3-Chloropropylmethyldichlorosilane (Gelest, 97%) was stirred over calcium hydride at room temperature for 24 h, degassed on vacuum line before distillation into scaled ampules which were then flame-sealed off the line. Methanol (Fisher Scientific, Certified ACS) was degassed on the vacuum line before distillation into ampules and flame-sealed. Chloroform (Fisher Scientific, Certified ACS), hexanes (Fisher Scientific, Certified ACS), tetrahydrofuran (THF, EMD, ACS grade), ethyl acetate (EA, Fisher Scientific, Certified ACS), *N,N*-dimethylformamide (anhydrous, 99.8%, Sigma-Aldrich), sodium azide (NaN_3, Sigma-Aldrich, 99%), copper(I) bromide (98%, Acros Organics), *N,N,N′,N″,N″*-pentamethyldiethylenetriamine (PMDETA, Sigma-Aldrich, 99%), 1-thioglycerol (Fluka, ≥ 98%), 2-hydroxy-4′-(2-hydroxyethoxy)-2-methylpropiophenone (Irgacure 2959, Sigma-Aldrich, 98%) were used as received. Silica gel (Sorbtech Technologies, 230–400 mesh) was activated by heating to 140°C for 12 h. VPOSS-alkyne was prepared as reported previously[41].

Characterizations

All of ^{1}H- and ^{13}C-NMR spectra were obtained in $CDCl_3$ (99.8% D, Sigma-Aldrich) at 30°C using a Varian NMRS 500 spectrometer equipped with an auto-sampling robot. For all ^{1}H-NMR experiments, the sample concentration was about 10–20 mg/mL; higher concentrations (*ca*. 50–80 mg/mL) were used for ^{13}C-NMR measurements. The ^{1}H-NMR spectra were referenced to the residual proton impurities in the $CDCl_3$ at δ = 7.27 and ^{13}C-NMR spectra, referenced to $^{13}CDCl_3$ at δ = 77.00. For mPS-VPOSS, the integration ratio between the characteristic vinyl peaks on POSS at δ = 6.15–5.88 (21 H per VPOSS) and the peaks at δ = 7.40–6.32 (aromatic protons in PS) gives rise to a number-average degree of polymerization of the polymer block (DP). The calculated molecular weight ($M_{n,NMR}$) can then be obtained by the summation of $M_{n,Polymer}$ (DP × 104.1 g/mol for PS), $M_{Initiator}$ (114.2 g/mol for PS) and M_{XPOSS} (858.4 g/mol for VPOSS and 1615.5 g/mol for DPOSS, respectively, including the molecular weight of the silane linker).

Infrared spectra of the polymers were measured on an Excalibur Series FT-IR spectrometer (DIGILAB, Randolph, MA) by drop-casting sample films on a KBr plate from polymer solutions in THF (*ca.* 10 mg/mL). The samples were subsequently undergone evaporating solvent at room temperature *via* blowing air. The data were processed utilizing the Win-IR software equipped with the instrument.

Matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectra were obtained on a Bruker Ultraflex III TOF/TOF mass spectrometer (Bruker Daltonics, Billerica, MA), coupled with a Nd:YAG laser which emits at 355 nm. The chemical compound *trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile (DCTB, > 99%, Aldrich) was used as matrix in these MALDI-TOF MS experiments, and this compound was dissolved in $CHCl_3$ at a concentration of 20.0 mg/mL. Sodium trifluoroacetate (NaTFA) or silver trifluoroacetate (AgTFA) was applied as the cationizing agent and was prepared as the MeOH/$CHCl_3$ (1/3, *V*/*V*) solution at a concentration of 10.0 mg/mL. The matrix and cationizing agent solutions were mixed in a ratio of 10/1 (*V*/*V*). The final sample was prepared by first depositing 0.5 μL of matrix and salt mixture on the wells of a 384-well ground-steel plate, allowing the spots to dry and then, depositing 0.5 μL of each sample on a spot of dry matrix, and adding another 0.5 μL of matrix and salt mixture on top of the dry sample (the sandwich method)[44]. Mass spectra were collected in the reflection mode or linear mode, and the mass scale was calibrated externally utilizing a PMMA standard at the molecular weight region under investigation. Data analyses were performed with the Bruker's flexAnalysis software.

Size exclusion chromatograms (SEC) of the samples were obtained from a Waters 150-C Plus instrument equipped with three HR-Styragel columns [100 Å, mixed bed (50/500/10^3/10^4 Å), mixed bed (10^3, 10^4, 10^6 Å)], and a triple detector system including a differential viscometer (Viscotek 100), a differential refractometer (Waters 410), and a laser light scattering detector (Wyatt Technology, DAWN EOS, λ = 670 nm). The instrument was calibrated with polystyrene standards with molecular weights ranging from 580 g/mol to 841000 g/mol. The eluent was THF at a flow rate of 1.0 mL/min at 35°C. The sample solution was prepared in THF with a concentration of *ca.* 5–10 mg/mL depending on the molecular weights of polymers and was filtered through a 0.45 μm Teflon filter before the measurements. Data processing was *via* the work station software equipped with the system. Respective molecular weights from SEC experiments ($M_{n,SEC}$ and $M_{w,SEC}$) and polydispersity indexes (PDIs) were obtained from a working curve based on polystyrene standards.

Synthetic Procedures

mPS-Cl

The anionic polymerization was carried out in sealed glass reactors under high vacuum at room temperature. The synthesis was initialized by smashing the break-seal of the styrene ampule to add styrene (5.0 mL, 4.55 g, 43.7 mmol) into a benzene solution (*ca.* 50 mL) of *sec*-butyllithium (2.92 mmol). The resulting red solution was allowed to stir at 25°C overnight. A small aliquot of PSLi was taken by flame-sealing one ampule from the reactor and quenched by methanol to give the base PS. Then, 3-chloropropylmethyldichlorosilane (*ca.* 0.266 g, *ca.* 220 μL, *ca.* 1.39 mmol) was added by smashing the break-seal of the corresponding ampoule. The mixture was allowed to react at 25°C for 4 h before the addition of ethylene oxide (EO, 1.0 mL in 5 mL benzene,

20 mmol). After 10 min, the reaction was quenched by addition of methanol (2 mL). After 15 min, the solution was concentrated and precipitated into cold methanol to afford the crude product. The product was first purified by silica gel chromatography with toluene/hexane mixture (1/1, *V*/*V*) as the eluent and was then precipitated from THF solution into cold methanol three times. The solids were collected and dried under vacuum to afford mPS-Cl as a white powder (3.2 g). Yield: *ca.* 70%. ^{1}H-NMR ($CDCl_3$, 500 MHz, δ): 7.40–6.30 (m, 150H), 3.40–3.05 (m, 2H), 2.50–1.10 (m, 98H), 0.97 (m, 2H), 0.76–0.62 (m, 12H), 0.30–0.5 (m, 3H). ^{13}C-NMR ($CDCl_3$, 125 MHz, δ): 145.6–144.9, 129.1–125.4, 47.8, 46.2–40.4, 31.5, 30.5, 30.0, 29.8, 29.1, 28.8, 28.2, 19.9, 19.3, 18.6, 11.2, 10.8. FT-IR (KBr) ν (cm^{-1}): 3061, 3027, 2925, 2853, 1944, 1874, 1804, 1601, 1495, 1452, 1376, 1182, 1069, 1029, 908, 758, 699. MS (MALDI-TOF, *m/z*): calcd. mono-isotopic mass for [26mer·Ag-HCl]$^+$ ($C_{220}H_{234}AgSi$): 3010.7 Da, found 3011.2 Da. $M_{n,NMR}$ = 3.3 kg/mol. SEC: $M_{n,SEC}$ = 3.2 kg/mol, $M_{w,SEC}$ = 3.3 kg/mol, PDI = 1.03. For the base PS: $M_{n,SEC}$ = 1.5 kg/mol, $M_{w,SEC}$ = 1.6 kg/mol PDI = 1.07.

mPS-N_3

To a 50 mL round-bottom flask equipped with a magnetic stirring bar were added mPS-Cl (M_n = 3.3 kg/mol, PDI = 1.03, 500 mg, 0.15 mmol), NaN_3 (98 mg, 1.5 mmol) and anhydrous DMF (3 mL). The mixture was heated to 60°C and stirred overnight. The mixture gradually turned turbid. The mixture was allowed to cool to room temperature and 20 mL CH_2Cl_2 was added. The resulting mixture was washed with water (50 mL × 2), brine (50 mL), dried over Na_2SO_4, concentrated under vacuum, and precipitated into cold methanol. The white solids were collected and dried under vacuum to afford mPS-N_3 (460 mg). Yield: 92%. ^{1}H-NMR ($CDCl_3$, 500 MHz, δ): 7.40–6.30 (m, 150H), 3.10–2.70 (m, 2H), 2.50–1.10 (m, 98H), 0.97 (m, 2H), 0.76–0.62 (m, 12H), 0.30–0.5 (m, 3H). ^{13}C-NMR ($CDCl_3$, 125 MHz, δ): 145.6–144.9, 129.1–125.4, 54.3, 46.2–40.4, 31.5, 30.5, 30.0, 29.8, 29.1, 28.8, 28.2, 22.9, 19.9, 19.3, 18.6, 11.2, 8.6, 7.0. FT-IR (KBr) ν (cm^{-1}): 3061, 3027, 2925, 2852, 2095 (azide group), 1943, 1869, 1802, 1733, 1602, 1493, 1451, 1375, 1181, 1070, 1028, 908, 756, 699. MS (MALDI-TOF, *m/z*): calcd. average mass for [26mer·Ag]$^+$ ($C_{220}H_{235}AgN_3Si$): 3057.2 Da, found 3057.6 Da. $M_{n,NMR}$ = 3.3 kg/mol. SEC: $M_{n,SEC}$ = 3.2 kg/mol, $M_{w,SEC}$ = 3.3 kg/mol, PDI = 1.03.

mPS-VPOSS

This reaction was performed in a similar procedure to previous report[41]. To a 100 mL Schlenk flask equipped with a magnetic stir bar were added VPOSS-alkyne (100 mg, 0.14 mmol, 1.0 eq.), mPS-N_3 (M_n = 3.3 kg/mol, PDI = 1.03, 462 mg, 0.14 mmol, 1.0 eq.), CuBr (1 mg, 0.007 mmol, 0.05 eq.), and freshly distilled toluene (10 mL). The resulting solution was degassed by three freeze-pump-thaw cycles before the addition of PMDETA (20 mg, 24.1 μL, 1.0 eq.) *via* pipette. The mixture was further degassed by one cycle, and was then stirred at room temperature for 12 h. After the reaction was complete, the solution was directly transferred onto a silica gel column. Toluene was first used as the eluent to fully remove the unreacted starting materials, then a mixture of toluene and ethyl acetate (1/1, *V*/*V*) was used to wash the product off the column. After solvent removal, the crude product was precipitated into cold MeOH, collected by vacuum filtration, and dried under vacuum to afford mPS-VPOSS as a white powder (478 mg). Yield: *ca.* 85%. ^{1}H-NMR ($CDCl_3$, 500 MHz, δ): 7.40–6.30 (m, 150H), 6.25–5.80 (m, 21H), 4.34 (m, 2H), 4.20–3.75 (m, 2H), 3.05 (m, 2H), 2.75 (m, 2H), 2.50–1.00 (m, 103H), 0.76–0.62 (m, 12H), 0.30–0.5 (m, 3H). ^{13}C-NMR ($CDCl_3$, 125 MHz, δ): 172.6, 146.0–144.9, 137.1, 137.0, 129.1–124.6, 120.5, 60.7, 52.8, 46.2–40.4, 33.7, 31.5, 30.3, 29.9, 29.8, 28.8, 28.2, 24.2, 20.9, 19.9, 19.2, 18.7, 18.5, 13.2, 11.2–10.8. FT-IR (KBr) ν (cm^{-1}): 3083, 3061, 3027, 2925, 2853, 1945, 1873, 1804, 1729, 1602, 1549, 1493, 1452, 1408, 1365, 1275, 1122 (Si—O—Si asymmetric stretching), 1029, 1007, 971, 908, 760, 731, 699, 586. MS (MALDI-TOF, *m/z*): calcd. mono-isotopic mass for [26mer·Na]$^+$ ($C_{241}H_{265}N_3NaO_{14}Si_9$): 3699.8 Da, found 3700.0 Da. $M_{n,NMR}$ = 4.1 kg/mol. SEC: $M_{n,SEC}$ = 3.6 kg/mol, $M_{w,SEC}$ = 3.7 kg/mol, PDI = 1.02.

mPS-DPOSS

To an open vial without stirring bar were added mPS-VPOSS (M_n = 4.1 kg/mol, PDI = 1.03, 187 mg, 0.046 mmol, 1.0 eq.), 1-thioglycerol (50 mg, 0.46 mmol, 10.0 eq. per VPOSS, or 1.4 eq. per vinyl group), the photo-initiator Irgacure 2959 (1 mg, 0.0045 mmol, 0.10 eq. per VPOSS, or 0.014 eq. per vinyl group), and a

minimum amount of THF (about 2 mL) to fully dissolve the solids. The reaction was complete after irradiation by 365 nm UV light for 15 min. The mixture was then precipitated into a cold mixture of MeOH and water (1/1, *V*/*V*) and the precipitates were collected and dried under vacuum to afford the product as a white powder (179 mg). Yield: *ca.* 80%. ^{1}H-NMR ($CDCl_3$, 500 MHz, δ): 7.40–6.30 (m, 150H), 4.75–3.90 (m, 16H), 3.85–3.40 (m, 23H), 2.97 (m, 2H), 2.80–2.40 (m, 30H), 2.40–0.80 (m, 117H), 0.76–0.62 (m, 12H), 0.30–0.5 (m, 3H). ^{13}C-NMR ($CDCl_3$, 125 MHz, δ): 172.9, 146.0–144.9, 129.1–124.6, 120.6, 71.1, 65.4, 60.8, 52.9, 46.2–40.4, 35.3, 33.6, 31.5, 30.3, 29.8, 29.6, 28.8, 26.7, 20.7, 19.8, 19.2, 18.6, 18.5, 12.8, 11.3–10.8. FT-IR (KBr) ν (cm^{-1}): 3390 (br), 3061, 3026, 2925, 1734, 1649, 1601, 1581, 1493, 1453, 1385, 1283, 1182, 1118 (Si—O—Si asymmetric stretching), 1030, 908, 758, 699. MS (MALDI-TOF, *m/z*): calcd. mono-isotopic mass for $[26mer{\cdot}Na]^+$ ($C_{262}H_{321}N_3NaO_{28}S_7Si_9$): 4456.0 Da, found 4456.2 Da. $M_{n,NMR}$ = 4.9 kg/mol. SEC: $M_{n,SEC}$ = 4.4 kg/mol, $M_{w,SEC}$ = 4.5 kg/mol, PDI = 1.03.

RESULTS AND DISCUSSION

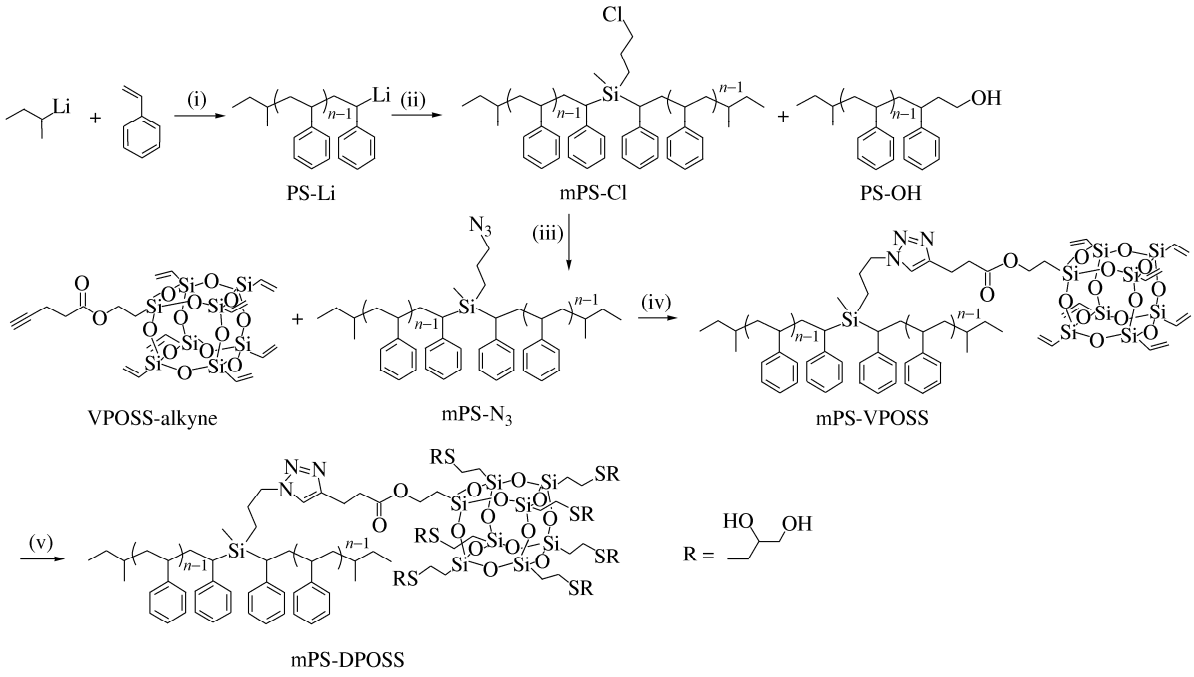
Anionic Synthesis of mPS-N_3

Living anionic polymerization of styrenic and dienic monomers initiated by alkyllithium in hydrocarbon solvents affords the most precise control over molecular weight, molecular weight distribution, composition, and molecular architecture of the resulting polymers[1–5]. The reaction of polymeric organolithium compounds with silyl halides is a well-established efficient functionalization method for anionic polymers[1]. In-chain functionalized PS can be achieved by the use of a functional dichlorosilane derivative as the coupling agent provided that the attached functional group should be compatible with the reaction conditions[3, 13]. Previously, a silyl-hydride bond has been introduced by the coupling reaction and later converted to a cyano group at the middle of the chain by hydrosilylation[13]. Due to the reactivity of azide groups, it is difficult to directly introduce azide groups during living functionalization. But it can be converted from an alkyl halide by nucleophilic substitution. Considering the lower reactivity of alkyl chloride (especially when compared to silyl chlorides), 3-chloropropyldichloromethylsilane is selected as the silane linker[9]. The high selectivity allows efficient coupling between the silyl halide and poly(styryl)lithium and the low reactivity of alkyl chloride retains the intact chloro functionality at relatively short time scale for future transformation into the "clickable" azide group[9, 45].

The synthesis is outlined in Scheme 1. The anionic polymerization and the subsequent coupling reaction took place at room temperature. Slightly excess PSLi was added (1:0.48) to ensure full consumption of the silane linker. It is found that the optimal reaction time is 4 h so that all silane linker has reacted while there is no significant side reaction between excess PSLi and the alkyl chloro group. After 4 h, the excess amount of PSLi was end-capped with ethylene oxide and quenched with methanol to introduce a polar hydroxyl group at the chain-end. The polarity of the excess PS is thus very different from the nonpolar coupled product, and separation was conveniently achieved by flash chromatography using the mixture of toluene and hexane (1/1, *V*/*V*) as the eluent. The first eluted product was the desired mPS-Cl, which was then thoroughly characterized by various routine techniques.

From the SEC curves of the base PS and the purified product (as shown in Fig. 1), it is obvious that the elution profile of mPS-Cl is narrowly distributed and symmetric. Moreover, it shifts to a much smaller retention volume compared to that of the base PS, indicating the increase of molecular weight upon the coupling reaction. The determined number-average molecular weights in SEC experiments ($M_{n,SEC}$) of these two polymers are 1.5k and 3.2k, respectively, matching well with the doubled M_n of mPS-Cl after chemical coupling of the base PSLi with the silane linker. Polydispersity of the resulting mPS-Cl remains very low (PDI = 1.03 from the SEC measurement), suggesting the well-controlled nature of this reaction. In the ^{1}H-NMR spectrum (Fig. 2A), the hydrogens on the carbons adjacent to the chloro and silicon atoms can be clearly assigned. It is also evident in the MALDI-TOF mass spectrum (Fig. 3a) that a single major molecular weight distribution with mono-isotopic resolution can be observed. The distance between neighboring peaks is found to be 104.1 Da, indicating the mass of one styrene repeating unit. The observed *m/z* values match well with the calculated ones. For example, the

theoretical *m/z* value for 26mer [26mer·Ag-HCl]$^+$ is 3010.7 Da, and the found value is 3011.2 Da. All these data support the successful coupling reaction between PSLi and the silane linker.



Scheme 1 Synthesis of mPS-DPOSS *via* living anionic polymerization and sequential "click" reactions
(i) Benzene, 25°C, overnight; (ii) (a) 3-chloropropylmethyldichlorosilane (0.48 eq.), benzene, 25°C, 4 h; (b) excess ethylene oxide, 10 min; and (c) methanol, 15 min; isolated yield: *ca*. 70%; (iii) NaN_3, DMF, 60°C, 92%; (iv) CuBr, PMDETA, toluene, r.t., *ca*. 85%; (v) 1-thioglycerol (10 eq.), Irgacure 2959, THF, *hv*, 15 min, *ca*. 80%

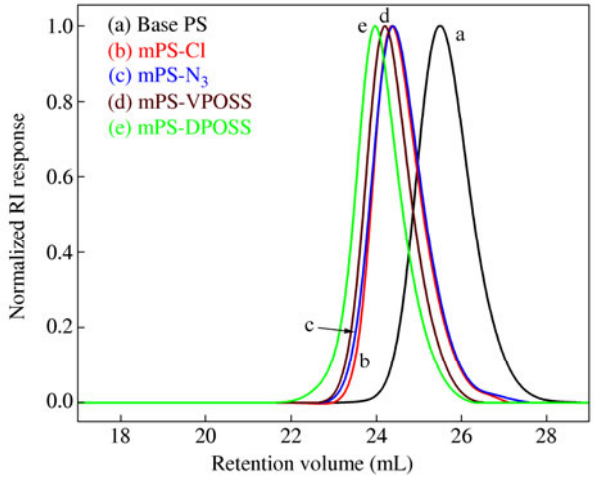


Fig. 1 SEC overlay of (a) base PS, (b) mPS-Cl, (c) mPS-N_3, (d) mPS-VPOSS, and (e) mPS-DPOSS

The successful anionic synthesis of mPS-Cl provides the precursor of a "clickable" middle-chain functionalized PS. The chemical transformation from a chloro group to an azide group has been reported in many publications[46]. Due to the relatively low reactivity of the chloro group, the reaction was conducted at elevated temperature (60°C) to accelerate the nucleophilic substitution reaction between mPS-Cl and sodium azide. After 24 h, a new peak characteristic of the azide group (2095 cm^{-1}, see Fig. 4b) appears in the FT-IR

spectrum. The transformation is further supported by the up-field shift of the resonance signal of proton a in ^{1}H-NMR spectrum from δ = 3.40–3.05 to 3.10–2.70 (Figs. 2A and 2B). In the SEC overlay (Fig. 1), the traces from mPS-Cl and mPS-N_3 essentially overlap with each other, because the difference between the two is only one functional group.

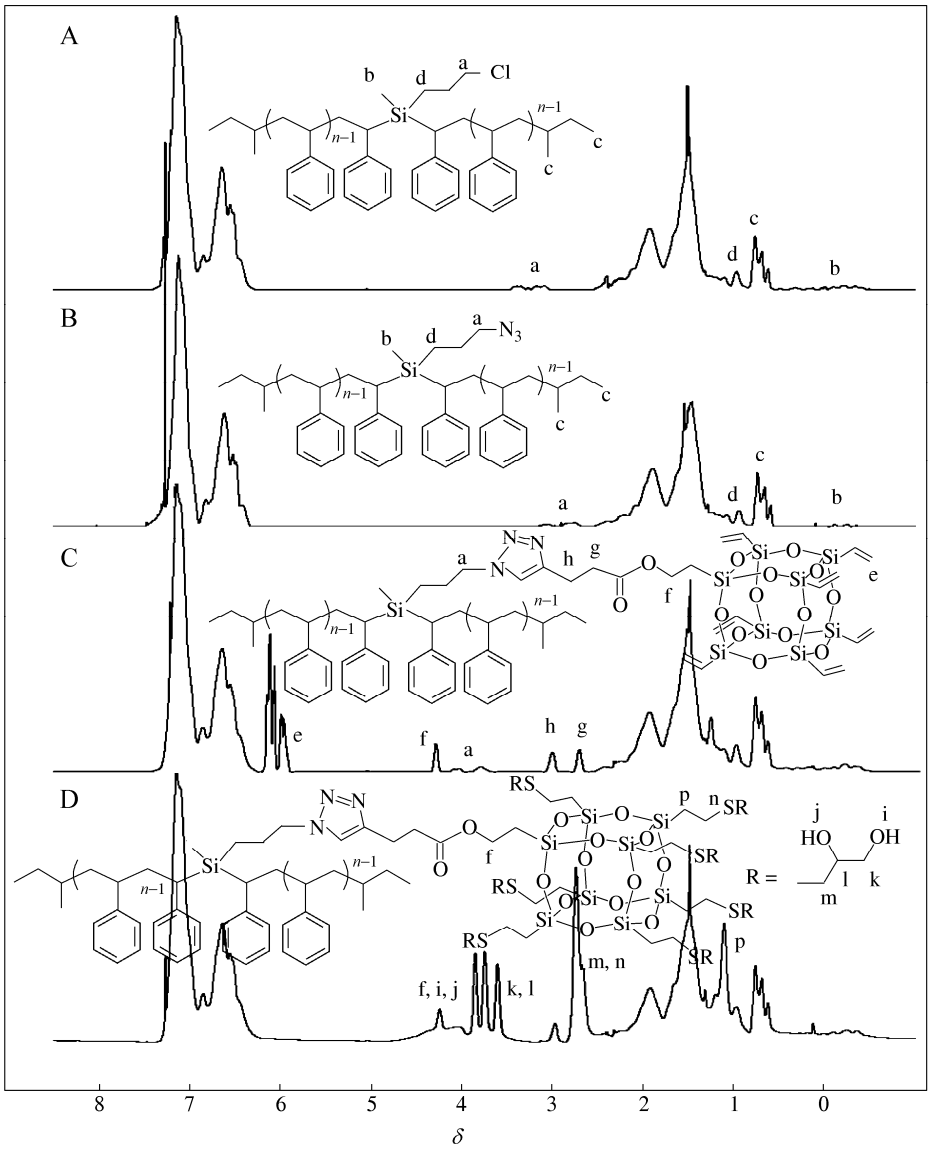


Fig. 2 ^{1}H-NMR spectra of (A) mPS-Cl, (B) mPS-N_3, (C) mPS-VPOSS and (D) mPS-DPOSS

The structure of mPS-N_3 is further examined by MALDI-TOF mass spectroscopy. As it is known that in reflection mode azide groups may decompose to lose one unit of N_2[47], the measurement was thus conducted in linear mode. Although the result was obtained without isotopic resolution in linear mode, a single molecular weight distribution was indeed observed. Moreover, the found average molecular weights are in good agreement with the calculated values (see Fig. 3b). These results prove the existence of azide groups and the complete reaction. The mPS-N_3 serves as a versatile building block to synthesize polymers of various architectures by "click" chemistry.

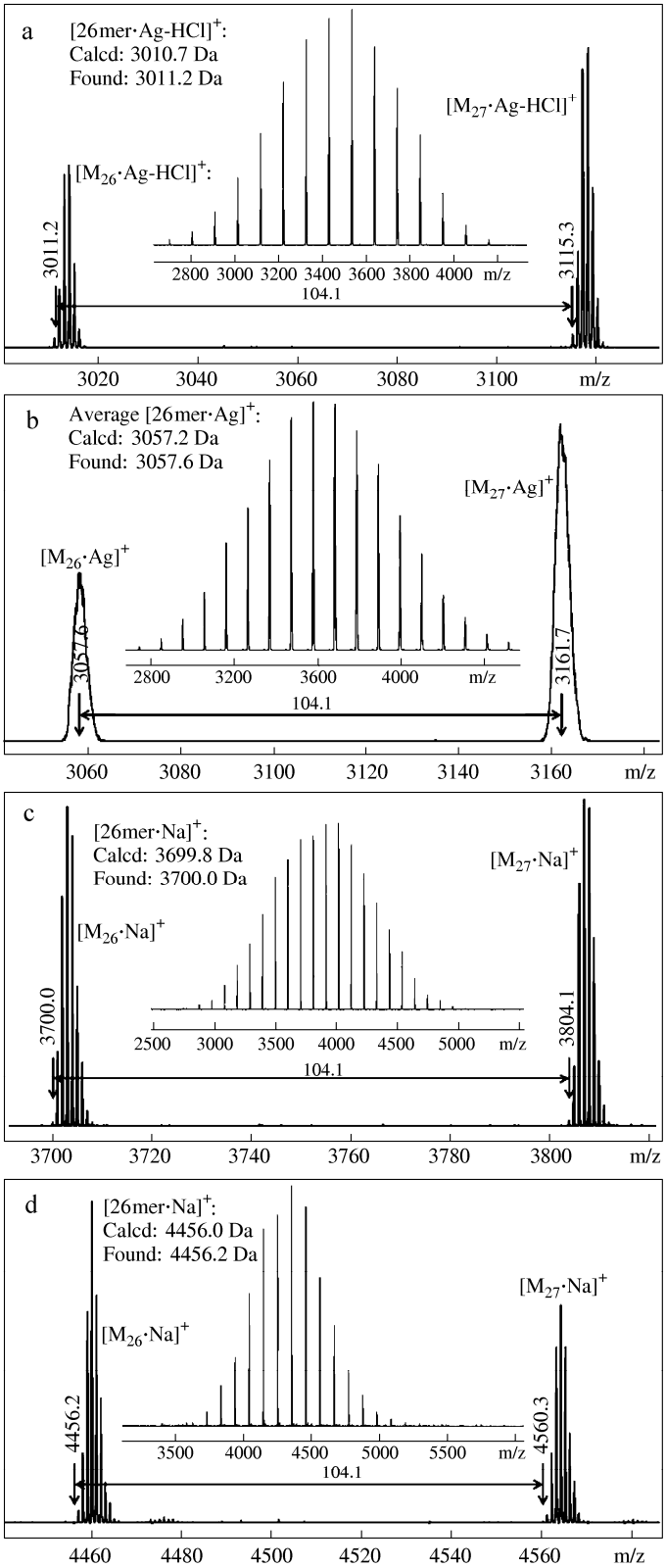


Fig. 3 MALDI-TOF MS spectra of (a) mPS-Cl, (b) mPS-N_3, (c) mPS-VPOSS and (d) mPS-DPOSS
The spectrum in (b) was obtained in linear mode, while the other three spectra were obtained in reflection mode.

Sequentially "Clicking" mPS-N_3 into Shape Amphiphiles

The emergence of "click" chemistry provides a modular design strategy towards complex functional materials with varied compositions from a library of simple building blocks[19, 20, 48]. The high efficiency and functional group tolerance of click reactions make them especially suitable as GFMs in post-polymerization modifications[18]. To demonstrate mPS-N_3 as a "clickable" building block in the library, a shape amphiphile resembling "giant lipids"[16, 17, 34, 35] was constructed from mPS-N_3 in two steps following a sequential "click" strategy[41, 42].

Shape amphiphiles are built from building blocks with incompatible packing geometries and distinct interaction parameters[33, 49–52]. Recently, our group has focused on the study of shape amphiphiles composed of polymer chain tethered molecular nanoparticles (MNPs). Various molecular architectures have been reported, including POSS tethered with one or two tails, which are referred to as "giant surfactant"[14, 15] or "giant lipid"[16, 17, 34, 35], respectively. Different from the reported synthetic methods for POSS-based "giant lipids", which were both based on the "growing-from" strategy[16, 17], the synthesis here combines the advantages of living anionic polymerization and "click" reactions, and is yet another example of our recently reported sequential "click" strategy to shape amphiphiles[41, 42]. The model reaction between mPS-N_3 and the reported VPOSS-alkyne[41] was first performed to afford an in-chain VPOSS-functionalized PS (Scheme 1) that was further modified by thiol-ene "click" reaction on the POSS cage.

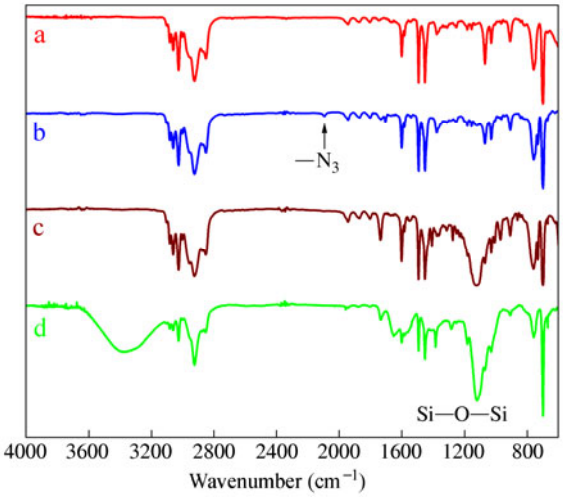


Fig. 4 FT-IR spectra of (a) mPS-Cl, (b) mPS-N_3, (c) mPS-VPOSS and (d) mPS-DPOSS

Following the published protocol, the CuAAC reaction proceeded efficiently at room temperature and the product was purified by flash column chromatography followed by precipitation into cold methanol. The attachment of VPOSS onto the middle-chain position of the PS chain is evidenced by results from various characterization techniques. FT-IR spectrum (Fig. 4c) shows complete disappearance of the peak from the azide group (2095 cm^{-1}) and the appearance of a strong peak at 1122 cm^{-1}, which is attributed to the asymmetric stretching of the Si—O—Si backbone of the POSS cage. In ^{1}H-NMR spectrum (Fig. 2C), the peaks ascribed to the vinyl groups on POSS are shown at δ = 6.25–5.80. Moreover, all the peaks in Fig. 2(C) can be ambiguously assigned. In ^{13}C-NMR spectrum (Fig. 5c), the vinyl carbons show their resonance at δ = 137.1 (marked with a star in Fig. 5c) and δ = 128.5 (overlapped with protons of PS). The increase of molecular weight by VPOSS modification is reflected by the shift of SEC peak to a smaller retention volume (Fig. 1). In MALDI-TOF MS spectroscopy (Fig. 3c), a single molecular weight distribution is observed, and the found molecular weights match well with the calculated values (Table 1). Based on all these evidences, the triazole linkage between VPOSS and PS is formed without a doubt.

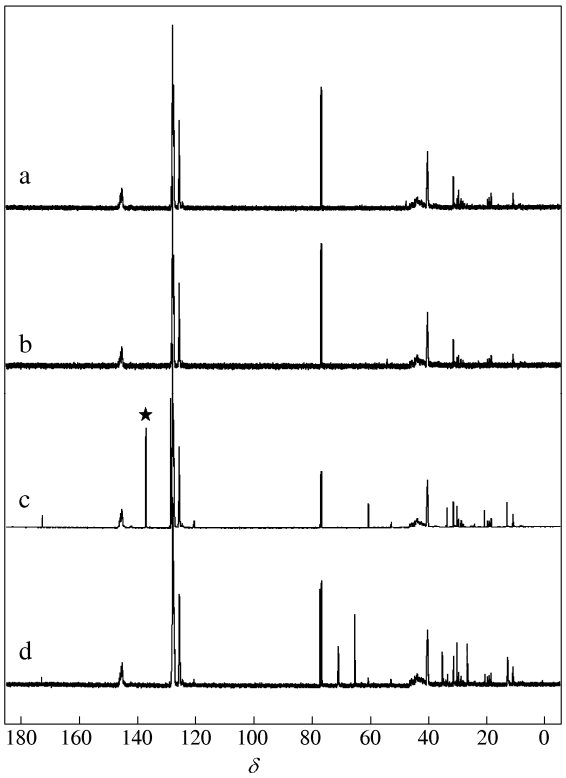


Fig. 5 ^{13}C-NMR spectra of (a) mPS-Cl, (b) mPS-N_3, (c) mPS-VPOSS and (d) mPS-DPOSS
The star in (c) denotes peaks from the vinyl groups on the POSS cage.

Table 1. Summary of molecular characterizations

Sample	Molecular formula	M_{Calcd} (Da)	M_{Found} (Da)	$M_{n,NMR}$[d] (kg/mol)	$M_{n,SEC}$[e] (kg/mol)	$M_{w,SEC}$[e] (kg/mol)	PDI[e]
mPS-Cl	$C_{220}H_{234}AgSi$[a]	3010.7[a]	3011.2[a]	3.3	3.2	3.3	1.03
mPS-N_3	$C_{220}H_{235}AgN_3Si$[b]	3057.2[b]	3057.6[b]	3.3	3.2	3.3	1.03
mPS-VPOSS	$C_{241}H_{265}N_3NaO_{14}Si_9$[c]	3699.8[c]	3700.0[c]	4.1	3.6	3.7	1.02
mPS-DPOSS	$C_{262}H_{321}N_3NaO_{28}S_7Si_9$[c]	4456.0[c]	4456.2[c]	4.9	4.4	4.5	1.03

[a] These data are based on 26mer with a silver ion losing one unit of [HCl] ([26mer·Ag-HCl]$^+$); [b] These data are based on 26mer with a silver ion ([26mer·Ag]$^+$); [c] These data are based on 26mer with a sodium ion ([26mer·Na]$^+$); [d] Data in this column are calculated from ^{1}H-NMR results; [e] Data in these columns are obtained from SEC measurements.

The synthesized mPS-VPOSS is subjected to subsequent chemical modification by the thiol-ene reaction to install functional groups onto the POSS cage. As demonstrated in previous reports[14–17], various functional groups, such as carboxylic acids, hydroxyls and fluorinated alkyl chains, can be introduced by using different small-molecule thiols. 1-Thioglycerol was chosen as the model thiol to demonstrate the synthesis of a novel shape amphiphile (mPS-DPOSS). Irradiation of 365 nm UV light for 15 min was sufficient to fully consume all of the vinyl groups. Strong evidence from ^{1}H-NMR (Fig. 2D), ^{13}C-NMR (Fig. 5d), SEC (Fig. 1), FT-IR (Fig. 4d), and MALDI-TOF mass spectra (Fig. 3d) all support the success of this reaction. For example, the vinyl protons at δ = 6.25–5.80 fully disappear after the thiol-ene reaction and so was the vinyl sp^2 carbon resonance signal at δ = 137.1 in the ^{13}C-NMR spectrum (Figs. 5c and 5d). FT-IR spectrum shows a broad peak at *ca.* 3380 cm^{-1} which is attributed to hydrogen-bonding between the hydroxyl groups on DPOSS. In SEC overlay, the symmetric elution profile of mPS-DPOSS shifts to a smaller retention volume, indicating increased molecular weight after the introduction of hydroxyl groups. Again, MALDI-TOF MS spectrum shows a single molecular weight distribution and the observed molecular weight of [26mer·Na]$^+$ agrees well with the calculated

value (4456.0 Da versus 4456.2 Da). After the thiol-ene modification, the installment of hydroxyl groups on the POSS cage makes the final product mPS-DPOSS a model amphiphilic shape amphiphile. All of these molecular characterizations are summarized in Table 1.

CONCLUSIONS

In summary, a "clickable" middle-chain azide-functionalized PS has been designed and synthesized by living anionic polymerization, and it can be used as a building block for facile synthesis of a novel shape amphiphile, mPS-DPOSS, *via* sequential "click" reactions. The mPS-N_3 was synthesized by the coupling reaction of PSLi and 3-chloropropylmethyldichlorosilane linker, followed by the substitution reaction with sodium azide. The coupling reaction occurred selectively between PSLi and silyl chloride and the removal of excess PS is facilitated by end-capping with ethylene oxide. The resulting mPS-N_3 was then reacted with VPOSS-alkyne to link VPOSS onto the PS chain. Subsequent thiol-ene reaction installed the hydroxyl groups onto the POSS cage, introducing chemical amphiphilicity to the final product (mPS-DPOSS). All the products were unambiguously characterized by various techniques. The final product, mPS-DPOSS, resembles the "giant lipid" architecture, *i.e*. a polar head tethered with two polymer tails. The study on its self-assembly behaviors and physical structures is ongoing in our group. This synthetic approach is highly efficient and modular. It demonstrates the "click" philosophy of facile complex molecule construction from a library of simple building blocks and also suggests that mPS-N_3 can be used as a versatile "clickable" motif in polymer science for the precision synthesis of complex macromolecules.

REFERENCES

1 Hsieh, H.L. and Quirk, R.P., "Anionic polymerization: principles and practical applications", Marcel Dekker, New York, 1996
2 Baskaran, D. and Muller, A.H.E., Prog. Polym. Sci., 2007, 32: 173
3 Hadjichristidis, N., Pitsikalis, M., Pispas, S. and Iatrou, H., Chem. Rev., 2001, 101: 3747
4 Quirk, R.P., Yoo, T., Lee, Y., Kim, J. and Lee, B., Adv. Polym. Sci., 2000, 153: 67
5 Tasdelen, M.A., Kahveci, M.U. and Yagci, Y., Prog. Polym. Sci., 2011, 36: 455
6 Quirk, R.P., Mathers, R.T., Ma, J.J., Wesdemiotis, C. and Arnould, M.A., Macromol. Symp., 2002, 183: 17
7 Quirk, R.P. and Ma, J.J., J. Polym. Sci., Part A: Polym. Chem., 1988, 26: 2031
8 Quirk, R.P., Kim, H., Polce, M.J. and Wesdemiotis, C., Macromolecules, 2005, 38: 7895
9 Bellas, V. and Rehahn, M., Macromol. Rapid Commun., 2007, 28: 1415
10 Quirk, R.P., Janoski, J., Chowdhury, S.R., Wesdemiotis, C. and Dabney, D.E., Macromolecules, 2009, 42: 494
11 Zhang, W.B., Sun, B., Li, H., Ren, X., Janoski, J., Sahoo, S., Dabney, D.E., Wesdemiotis, C., Quirk, R.P. and Cheng, S.Z.D., Macromolecules, 2009, 42: 7258
12 Li, Y.W., Zhang, W.B., Janoski, J.E., Li, X.P., Dong, X.H., Wesdemiotis, C., Quirk, R.P. and Cheng, S.Z.D., Macromolecules, 2011, 44: 3328
13 Quirk, R.P., Janoski, J., Chowdhury, S.R., Wesdemiotis, C. and Dabney, D.E., Macromolecules, 2008, 42: 494
14 Yu, X., Zhong, S., Li, X., Tu, Y., Yang, S., Van Horn, R.M., Ni, C., Pochan, D.J., Quirk, R.P., Wesdemiotis, C., Zhang, W.B. and Cheng, S.Z.D., J. Am. Chem. Soc., 2010, 132: 16741
15 Zhang, W.B., Li, Y., Li, X., Dong, X., Yu, X., Wang, C.L., Wesdemiotis, C., Quirk, R.P. and Cheng, S.Z.D., Macromolecules, 2011: 2589
16 He, J., Yue, K., Liu, Y., Yu, X., Ni, P., Cavicchi, K.A., Quirk, R.P., Chen, E.Q., Cheng, S.Z.D. and Zhang, W.B., Polym. Chem., 2012, 3: 2112
17 Li, Y., Dong, X.H., Guo, K., Wang, Z., Chen, Z., Wesdemiotis, C., Quirk, R.P., Zhang, W.B. and Cheng, S.Z.D., ACS Macro. Lett., 2012, 1: 834

18 Kolb, H.C., Finn, M.G. and Sharpless, K.B., Angew. Chem. Int. Ed., 2001, 40: 2004
19 Iha, R.K., Wooley, K.L., Nystrom, A.M., Burke, D.J., Kade, M.J. and Hawker, C.J., Chem. Rev., 2009, 109: 5620
20 Kempe, K., Krieg, A., Becer, C.R. and Schubert, U.S., Chem. Soc. Rev., 2012, 41: 176
21 Meldal, M. and Tornøe, C.W., Chem. Rev., 2008, 108: 2952
22 Hoyle, C.E. and Bowman, C.N., Angew. Chem. Int. Ed., 2010, 49: 1540
23 Hoyle, C.E., Lowe, A.B. and Bowman, C.N., Chem. Soc. Rev., 2010, 39: 1355
24 Lowe, A.B., Polym. Chem., 2010, 1: 17
25 Gao, H. and Matyjaszewski, K., J. Am. Chem. Soc., 2007, 129: 6633
26 Touris, A. and Hadjichristidis, N., Macromolecules, 2011, 44: 1969
27 Sugai, N., Heguri, H., Ohta, K., Meng, Q.Y., Yamamoto, T. and Tezuka, Y., J. Am. Chem. Soc., 2010, 132: 14790
28 Touris, A., Mays, J.W. and Hadjichristidis, N., Macromolecules, 2011, 44: 1886
29 Wang, G.W., Hu, B., Fan, X.S., Zhang, Y.N. and Huang, J.L., J. Polym. Sci., Part A: Polym. Chem., 2012, 50: 2227
30 Takano, A., Furutani, T. and Isono, Y., Macromolecules, 1994, 27: 7914
31 Quirk, R.P., Wang, S.F., Foster, M.D., Wesdemiotis, C. and Yol, A.M., Macromolecules, 2011, 44: 7538
32 Glotzer, S.C., Science, 2004, 306: 419
33 Glotzer, S.C., Horsch, M.A., Iacovella, C.R., Zhang, Z., Chan, E.R. and Zhang, X., Curr. Opin. Colloid Interface Sci., 2005, 10: 287
34 Yu, X., Zhang, W.B., Yue, K., Li, X., Liu, H., Xin, Y., Wang, C.L., Wesdemiotis, C. and Cheng, S.Z.D., J. Am. Chem. Soc., 2012, 134: 7780
35 Dong, X.H., Zhang, W.B., Li, Y., Huang, M., Zhang, S., Quirk, R.P. and Cheng, S.Z.D., Polym. Chem., 2012, 3: 124
36 Voronkov, M. and Lavrent'yev, V., Top. Curr. Chem., 1982, 102: 199
37 Laine, R.M., J. Mater. Chem., 2005, 15: 3725
38 Li, G., Wang, L., Ni, H. and Pittman, C.U., J. Inorg. Organomet. Polym., 2001, 11: 123
39 Phillips, S.H., Haddad, T.S. and Tomczak, S.J., Curr. Opin. Solid State Mater. Sci., 2004, 8: 21
40 Wu, J. and Mather, P.T., Polym. Rev., 2009, 49: 25
41 Yue, K., Liu, C., Guo, K., Yu, X., Huang, M., Li, Y., Wesdemiotis, C., Cheng, S.Z.D. and Zhang, W.-B., Macromolecules, 2012, 45: 8126
42 Yue, K., Liu, C., Guo, K., Wu, K., Dong, X.-H., Liu, H., Huang, M., Wesdemiotis, C., Cheng, S. Z. D. and Zhang, W.-B., Polym. Chem., 2012: DOI: 10.1039/C2PY20881D
43 Gilman, H. and Cartledge, F.K., J. Organomet. Chem., 1964, 2: 447
44 Hadjichristidis, N., Iatrou, H., Pispas, S. and Pitsikalis, M., J. Polym. Sci., Part A: Polym. Chem., 2000, 38: 3211
45 Gunes, K., Isayev, A.I., Li, X.P. and Wesdemiotis, C., Polymer, 2010, 51: 1071
46 Bellas, V. and Rehahn, M., Macromol. Chem. Phys., 2009, 210: 320
47 Zhang, W.B., Tu, Y., Ranjan, R., van Horn, R.M., Leng, S., Wang, J., Polce, M.J., Wesdemiotis, C., Quirk, R.P., Newkome, G.R. and Cheng, S.Z.D., Macromolecules, 2008, 41: 515
48 Li, Y., Hoskins, J.N., Sreerama, S.G. and Grayson, S.M., Macromolecules, 2010, 43: 6225
49 Zhang, S., Li, A., Zou, J., Lin, L.Y. and Wooley, K.L., ACS Macro. Lett., 2012, 1: 328
50 Zhang, Z.L., Horsch, M.A., Lamm, M.H. and Glotzer, S.C., Nano Lett., 2003, 3: 1341
51 Horsch, M.A., Zhang, Z. and Glotzer, S.C., Phys. Rev. Lett., 2005, 95: 056105
52 Iacovella, C.R., Horsch, M.A., Zhang, Z. and Glotzer, S.C., Langmuir, 2005, 21: 9488
53 Glotzer, S.C. and Solomon, M.J., Nat. Mater., 2007, 6: 557