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Synthesis of telechelic vinyl/allyl functional siloxane copolymers with structural control†

F. B. Madsen, I. Javakhishvili, R. E. Jensen, A. E. Daugaard, S. Hvilsted and A. L. Skov*

Multifunctional siloxane copolymers with terminal vinyl or allyl functional groups are synthesised through the borane-catalysed polycondensation of hydrosilanes and alkoxy silanes. Copolymers of varying molecular weights ($M_w = 13\,200–70\,300\, g\, mol^{-1}$), spatially well-distributed functional groups and high end-group fidelity are obtained in a facile and robust synthetic scheme involving polycondensation, end-group transformation and different functionalisation reactions such as Cu(i)-mediated azide–alkyne cycloaddition. Pendant alkyl chloride, alkyl azide, bromoisobutyryl, 4-nitrobenzene and 1-ethyl-imidazolium chloride fragments with programmable spatial distributions are incorporated in the copolymer backbones. NMR and FTIR spectroscopy as well as size exclusion chromatography corroborate the efficacy and versatility of this modular approach.

Introduction

The development of functional polymers is attracting increasing interest, due to a growing number of applications within nanotechnology, sustainability, biomedical- and energy-related fields. Functional polymers with specific control over architecture, polarity, functionality, solubility and reactivity are in especially high demand and controlled functionalisation is often used to change bulk and/or surface properties, in order to expand the application range of a given polymer.

Polysiloxanes, i.e. polymers containing Si–O–Si repeating units, are a group of polymers with significant industrial importance, since especially polysiloxane elastomers are used widely in advanced applications such as adhesives, membranes, implants and dielectric electro active polymers.2–6

The synthesis of polysiloxanes is generally accomplished through the nucleophilic substitution of chlorosilanes with water, to form low molecular weight linear silanols and cyclic siloxanes which are further reacted into high molecular weight polymers catalysed by acids or bases.7 Ring-opening polymerisation of cyclic siloxanes is very efficient and is extensively used to prepare siloxane homopolymers and random copolymers.8 A convenient method for more well-defined copolymers is the dehydrogenative coupling of organohydrosilanes with organohalosilanes, due to the high selectivity and easy removal of the hydrogen by-product. However, this type of reaction requires relatively high concentrations (≥0.1 mol%) of precious metal catalysts such as platinum, palladium, ruthenium or rhodium. Furthermore, only moderate molecular weight copolymers have been achieved, and undesired silanol self-condensation can occur and lead to disruption to a perfectly alternating copolymer structure.9–13

The Piers–Rubinsztajn reaction, which uses the tris(pentafluorophenyl)borane catalyst, offers an alternative route to structured siloxane copolymers. Piers et al. reported its use as a catalyst for reactions involving organohydrosilanes,14–16 while Rubinsztajn and Cella used it afterwards as a catalyst for siloxane homo- and copolymers.8,17,18 The Piers–Rubinsztajn reaction therefore refers to a tris(pentafluorophenyl)borane-catalysed reaction between a hydrosilane and an alkoxy silane, forming siloxanes with concomitant loss of an alkane – as seen in Scheme 1.19 The reaction is characterised by being exceptionally rapid, mild and efficient, since it can be carried out at ambient temperatures and uses low amounts of borane catalyst.

While functional polysiloxanes with, for example, amino-, chloro- and mercapto-functional groups are commercially available (e.g. from Gelest), they do not contain functional end-groups that allow them to be used in the synthesis of silicone elastomers. It is therefore difficult to obtain from commercially available raw materials elastomers with well distributing...
ted functional groups. Silicone elastomers are frequently prepared by platinum-catalysed hydroxylation reactions, where vinyl end-groups of polysiloxanes react with hydroxilane groups on siloxane cross-linkers. Functional elastomers can hence be prepared by using one of the components in excess and reacting vinyl- or hydride-functional molecules thereon. This approach, however, compromises network formation, meaning that inferior elastomer properties are thus a consequence.20

The aim of this work is to prepare spatially distributed and controlled functional siloxane copolymers through borane-catalysed polycondensation, which offers a rapid and efficient reaction method. The copolymers will contain vinyl or allyl end-groups, which will allow for platinum catalysed cross-linking reactions with hydroxilane cross-linkers. Furthermore, various functional groups along the backbone of the copolymers open up, for example, Williamson ether syntheses or copper-catalysed cycloaddition reactions of azides and alkynes (CuAAC) forming 1,4-disubstituted-1,2,3-triazoles, a so-called “click” reaction.21−24 Click reactions, which previously have been used to functionalise polymers in general25−28 and polysiloxanes in particular,29−32 are particularly efficient in the functionalization of polymers, as they do not form any by-products and yields are often high.

The prepared copolymers will vary greatly from the siloxane polymers originally prepared by Rubinsztajn and Cella,8,17,18 who prepared non-functional alternating aromatic and non-aromatic copolymers, in that the copolymers presented in this study will contain functional end-groups and reactive functional groups, which are spatially well-distributed through the use of dimethylsiloxane pre-polymer spacer units.

Herein we present the synthesis and characterisation of novel functional siloxane copolymers and describe how to tune the obtained molecular weights and the content of the spatially distributed functional units.

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**Experimental section**

**Materials and methods**

Hydride-terminated PDMS, DMS-H11 ($M_w \sim 1200 \text{ g mol}^{-1}$, as determined by $^1\text{H-NMR}$), 3-(chloropropyl)methylidimethylosilane, vinyldimethylsilane and allyldimethylsilane were acquired from Gelest Inc. Hydride-terminated PDMS ($M_w \sim 580 \text{ g mol}^{-1}$ as stated by supplier) was purchased from Sigma-Aldrich. All other chemicals were acquired from Sigma-Aldrich and used as received unless otherwise stated.

FTIR spectroscopy was conducted on PerkinElmer Spectrum One model 2000 Fourier Transform Infrared apparatus equipped with a universal attenuated total reflection accessory on a ZnSe/diamond composite. Spectra were recorded in the range of 4000−650 cm$^{-1}$, with 4 cm$^{-1}$ resolution and 16 scans. $^1\text{H}$- and $^{13}\text{C}$-NMR experiments were performed on a Bruker 300 MHz spectrometer in CDCl$_3$, while size-exclusion chromatography (SEC) was performed on a Tosoh EcoSEC HLC-8320GPC instrument equipped with RI and UV detectors and SDV Linear S columns from PSS, Mainz, Germany. Samples were run in toluene at 35 °C at a rate of 1 mL min$^{-1}$, and molar mass characteristics were calculated using WinGPC Unity 7.4.0 software and linear polydimethylsiloxane (PDMS) standards acquired from PSS, Mainz, Germany.

**Syntheses**

All reactions were carried out in a nitrogen atmosphere. Structures for $^{13}\text{C}$-NMR assignment can be found in the ESL†

**General procedure for Piers–Rubinsztajn polymerisation, α,ω-vinyl-pol([(chloropropyl)methylsiloxane-co-dimethylsiloxane]) (1).** 3-Chloropropylmethylidimethoxysilane (2.00 g, 10.9 mmol) was dissolved in dry heptane (20 mL) in a 250 mL two-neck round-bottomed flask. Hydride-terminated dimethylsiloxane (Aldrich, ~580 g mol$^{-1}$) (6.03 g, 10.4 mmol) was added and the mixture was stirred for 5 minutes. Tris(pentafluorophenyl)borane (0.6 mL, 0.04 M, 0.2 mol%) in dry toluene (2 mL) was added and methane gas developed. The mixture was stirred at RT for 1 hour, where after excess dimethoxymethylsiloxane (5.26 g, 43.7 mmol) was added, in order to quench any potentially remaining hydride groups and to ensure that all polymers possessed methoxy end-groups. The reaction mixture was stirred additionally for a couple of hours. The solvent and excess dimethoxymethylsiloxane (bp: 82 °C) were removed in vacuo at 45 °C with toluene, to give the product as a clear oil (7.42 g, 96.4%). IR (cm$^{-1}$): 2960 (C−H stretch); 1410 (Si–CH$_2$ stretch); 1260 (Si–CH$_3$ stretch); 1010 (Si−O stretch). $^1\text{H}$ NMR (CDCl$_3$, δ$_{H}$, ppm): 0.08−0.09 (m, CH$_3$−Si), 0.63 (m, −Si−CH$_2$−CH$_2$−), 1.83 (m, −CH$_2$−CH$_2$−CH$_2$), 3.49 (s, 6H, −O−CH$_3$), 3.50 (t, $J$ = 6.9 Hz, Cl−CH$_2$−CH$_2$). $^{13}\text{C}$-NMR (CDCl$_3$, δ$_{C}$, ppm): −0.51 to 1.54 (e + f), 15.06 (b), 26.78 (c), 47.59 (d), 49.90 (a).

**General procedure for end-capping, α,ω-vinyl-pol([(chloropropyl)methylsiloxane-co-dimethylsiloxane]) (2a−7).** Copolymer 1 (1.5 g, ~0.073 mmol methoxy end-groups) was dissolved in dry heptane (20 mL) in a 250 mL two-neck round-bottomed flask. Vinyldimethylsiloxane (1.89 g, 21.8 mmol) was added and the mixture was stirred at RT overnight after which $^1\text{H}$-NMR was used in order to confirm the removal of methoxy groups and conversion to vinyl groups. Neutral aluminium oxide (5 g) was added to the reaction mixture to remove the tris(pentafluorophenyl)borane catalyst, and the solution was then filtered through 0.45 μm PFTE filters. The solvent and excess vinyldimethylsiloxane reagent were removed in vacuo, to give the product as a clear oil (1.35 g, 90.3%). IR (cm$^{-1}$): 2960 (C−H stretch); 1410 (Si−CH$_3$ stretch); 1260 (Si−CH$_3$ stretch); 1010 (Si−O stretch). $^1\text{H}$ NMR (CDCl$_3$, δ$_{H}$, ppm): 0.08−0.09 (m, CH$_3$−Si), 0.62 (m, −Si−CH$_2$−CH$_2$−), 1.82 (m, −CH$_2$−CH$_2$−CH$_2$), 3.50 (t, $J$ = 6.9 Hz, Cl−CH$_2$−CH$_2$), 5.74 (dd, 2H, $^2J$ = 4.2 Hz, $^3J$ = 20 Hz, CH=CH$_3$), 5.94 (dd, 2H, $^2J$ = 4.2 Hz, $^3J$ = 15 Hz, CH=CH$_3$), 6.12 (dd, 2H, $^2J$ = 16 Hz, $^3J$ = 21 Hz, −CH=CH$_3$). $^{13}\text{C}$-NMR (CDCl$_3$, δ$_{C}$, ppm): −0.32 to 1.53 (e + d + h), 15.04 (e), 26.75 (f), 47.61 (g), 131.86 (a), 139.10 (b).

α,ω-Allyl-pol([(chloropropyl)methylsiloxane-co-dimethylsiloxane]) (2b-1). The polymer was prepared according to the general end-capping procedure using 1 (3 g, 0.14 mmol...
methoxy end-groups) and allyldimethylsilane (4.38 g, 43.7 mmol) to give a clear oil (2.85 g, 95.1%). IR (cm⁻¹): 2960 (C-H stretch); 1630 (C=C stretch); 1410 (Si-CH3 stretch); 1260 (Si-CH2 stretch); 1010 (Si-O stretch). ¹H NMR (CDCl3, δH, ppm): -0.05 to 0.09 (m, CH2-Si), 0.62 (m, -Si-CH2-CH2-), 1.50 (d, 4H, J = 7.8 Hz, CH2-CH2-Si), 1.82 (m, -Si-CH2-CH2-Si), 3.50 (m, J = 6.9 Hz, CH2-CH2-CH2-). ¹³C-NMR (CDCl3, δC, ppm): -0.53 to 1.54 (d + e + i), 15.04 (f), 23.41 (c), 26.75 (g), 47.61 (h), 112.53 (a), 135.30 (b).

α,ω-Allyl-(azidopropyl)methylsiloxane-co-dimethyldisiloxane (3). Following a procedure adapted from Rambarran et al. 33 copolymer 2b-1 (0.75 g, ~1.02 mmol (chloropropyl)methylsiloxane units), NaN3 (0.35 g, 5.4 mmol) and tetrabutylammonium azide (0.03 g, 0.11 mmol) were dissolved in dry THF (10 mL) in a 100 mL round-bottomed flask. The reaction mixture was stirred under reflux for 48 hours. THF was removed in vacuo and the reaction mixture was re-dissolved in heptane (20 mL), washed with water (3 × 20 mL) and brine (1 × 20 mL), dried with MgSO4 and then filtered and concentrated in vacuo to afford a transparent, viscous liquid (0.67 g, 89.5%). IR (cm⁻¹): 2960 (C-H stretch); 1630 (C=C stretch); 1410 (Si-CH3 stretch); 1260 (Si-CH2 stretch); 1010 (Si-O stretch). ¹H NMR (CDCl3, δH, ppm): -0.05 to 0.09 (m, CH2-Si), 0.58 (m, -Si-CH2-CH2-), 1.50 (d, 4H, J = 8.1 Hz, CH2-CH2-Si), 1.65 (m, -Si-CH2-CH2-CH2-), 3.23 (m, J = 7.1 Hz, N-, CH2-CH2-Si), 4.83 (m, 4H, CH=CH2), 5.77 (m, 2H, CH=CH2). ¹³C-NMR (CDCl3, δC, ppm): -0.55 to 1.03 (d + e + i), 14.50 (f), 22.77 (g), 23.40 (c), 54.14 (h), 112.51 (a), 135.32 (b).

General procedure for CuAAC click reactions, synthesis of α,ω-allyl-(2-bromo-2-methylpropanoate)-1H-1,2,3-triazolepropyl)methylsiloxane-co-dimethyldisiloxane (4). (0.2 g, ~0.27 mmol (azidopropyl)methylsiloxane units) and propargyl-2-bromoisobutyrate (0.06 g, 0.28 mmol) were dissolved in dry THF (3.5 mL) in a 25 mL two-neck round-bottomed flask. CuI (0.006 g, 0.03 mmol) was subsequently added and Et3N (0.04 g, 0.43 mmol) was added drop-wise. The reaction was carried out at RT for 17 hours at which point FTIR confirmed the disappearance of the azide band at 2095 cm⁻¹. THF was evaporated and the reaction mixture was precipitated into cold methanol. The solvent was then decanted and the product was dried in vacuo, providing a dark-green viscous oil (0.18 g, 74.0% - after precipitation). IR (cm⁻¹): 2960 (C-H stretch); 1740 (C=O stretch); 1630 (C=C stretch); 1465 (C-H bend); 1370 (C-H bend); 1410 (Si-CH2 stretch); 1260 (Si-CH3 stretch); 1155 (C-O stretch); 1010 (Si-O stretch). ¹H NMR (CDCl3, δH, ppm): -0.06 to 0.13 (m, CH2-Si), 0.58 (m, -Si-CH2-CH2-), 1.54 (d, 4H, J = 7.8 Hz, CH2-CH2-Si), 1.82 (m, -Si-CH2-CH2-CH2-), 1.91 (s, Br-(CH2)3), 4.33 (m, J = 7.2 Hz, N-CH2-CH2-), 4.84 (m, 4H, CH=CH2), 5.33 (s, C=CH-O), 5.76 (m, 2H, CH=CH2), 7.61 (s, -C=CH-N). ¹³C-NMR (CDCl3, δC, ppm): -0.57 to 1.03 (m + e + q), 14.24 (f), 24.33 (g), 30.62 (p), 52.97 (h), 55.53 (o), 59.22 (k), 123.47 (i), 142.25 (j), 171.46 (l) (a, b and c not visible).

Synthesis of α,ω-vinylpoly((1-ethyl-1H-imidazol-3-ium chloride)-1H-1,2,3-triazolepropyl)methylsiloxane-co-dimethyldisiloxane (6). 2b-8 (14.0 g, ~19.1 mmol (chloropropyl)methylsiloxane units) and 1-ethylimidazole (9.19 g, 95.6 mmol) were mixed in a 250 mL two-neck round-bottomed flask. The reaction was carried out at 95 °C for 48 hours under reflux. The product was washed four times with toluene to remove excess 1-ethylimidazole and then dried in vacuo to give the product as an orange-brown oil (1.35 g, 46.0%). IR (cm⁻¹): 3085 (C=C stretch); 2965 (C-H stretch); 1630 (C=N, C=C stretch); 1565 (C=N ring stretch); 1455 (C-H bend); 1405 (Si-CH3 stretch); 1260 (Si-CH2 stretch); 1010 (Si-O stretch). ¹H NMR (CDCl3, δH, ppm): 0.073-0.16 (m, CH2-Si), 0.54 (m, -Si-CH2-CH2-), 1.60 (m, CH3-CH2-N), 1.94 (m, -CH2-CH2-CH2-), 4.35 (m, CH2-CH2-N), 4.43 (m, -N-CH2-CH2-CH2-), 5.73 (dd, 2H, J = 4.2 Hz, J = 20 Hz, CH=CH2), 5.94 (dd, 2H, J = 4.1 Hz, J = 15 Hz, CH=CH2), 6.13 (dd, 2H, J = 15 Hz, J = 20 Hz, CH=CH2), 7.42 (dd, J = 1.5 Hz, N-CH=CH-), 7.50 (dd, J = 1.5 Hz, N-CH=CH-), 10.9 (s, -N-CH=CH-N). ¹³C-NMR (CDCl3, δC, ppm): -0.66 to 1.09 (c + d + m), 13.60 (e), 15.53 (k), 24.24 (f), 45.10 (j), 52.07 (g), 121.34 (i), 122.15 (h), 136.54 (l) (a and b not visible).

Results and discussion

Siloxane copolymers with spatially well-distributed functional groups were prepared as illustrated in Scheme 2. Synthesis was accomplished through the tris(pentafluorophenyl)borane-catalysed Piers–Rubinsztajn reaction of 3-chloropropylmethyldimethoxysilane and hydride-terminated dimethyldihoxane pre-polymers to form methoxy-terminated copolymers 1. The borane-catalysed polycondensation of hydroxilanes and methoxysilanes to form 1 involves cleavage C-O and Si-H bonds while forming Si-O and C-H bonds in an exothermic reaction (ΔH ≈ ~250 kJ mol⁻¹). The reaction is performed at room temperature using low levels of BF3·OEt2 catalyst (<0.5 mol%). At higher catalyst concentrations (~1–5 mol%), hydrolysis reactions may compete with the Piers–Rubinsztajn polycondensation reaction. The reaction is almost instantaneous and is completed within a few minutes, but it was left to stir...
In $^1$H-NMR, resonance at $\delta = 4.7$ ppm disappeared, which was also corroborated by FTIR, where the distinctive stretch at 2125 cm$^{-1}$ was no longer present. In order to ensure at this stage that all polymers contained methoxy end-groups, significant amount of excess dimethoxydimethylsilane was added to the reaction mixture so that any remaining hydride groups would react. The excess dimethoxydimethylsilane was easily removed in vacuo.

The prepared copolymers were characterised by SEC, and molecular mass characteristics were calculated from linear polydimethylsiloxane standards. The results are summarised in Table 1. Two dimethylsiloxane pre-polymers of different molecular weights were used, in order to create copolymers with varying mol% of the (chloropropyl)methylsiloxane unit and with different spacer lengths between the functional groups. The molecular weights of the final copolymers were varied furthermore by changing the stoichiometry between the hydrosilane pre-polymers and the methoxysilane compound. According to standard polycondensation theory, the highest molecular weight would be obtained when using stoichiometries closest to unity. The highest molecular weight is obtained when using a stoichiometry of hydrosilane–methoxysilane of 0.95/1, with a molecular weight of $M_w = 70 \text{,}000$ g mol$^{-1}$. For the pre-polymer of $M_w \sim 580$ g mol$^{-1}$ the highest molecular weight was obtained using the stoichiometry of hydrosilane–methoxysilane of 1/0.95, where $M_w = 56 \text{,}000$ g mol$^{-1}$ was attained.

In order to test the reproducibility of the borane-catalysed polycondensations a reaction with the pre-polymer of $M_w \sim 1200$ g mol$^{-1}$ was repeated. As seen in Table 1, entries 2a-2 and 2a-3 were prepared using similar reaction conditions, and SEC provided comparable results for both experiments. This shows that the polycondensation reaction is quite robust when using similar reaction conditions.

The aim of this study was to create functional copolymers with molecular weights suitable for silicone elastomer synthesis. The best elastomer properties are usually obtained when using polymers with molecular weights of $M_w \sim 20\text{,}000$–30\text{,}000 g mol$^{-1}$. Molecular weights in this range were obtained for copolymer 2a-1 with a stoichiometric ratio of hydrosilane–methoxysilane of 0/1.9 using the pre-polymer of $M_w \sim 1200$ g mol$^{-1}$, where a molecular weight of $M_w = 25 \text{,}000$ g mol$^{-1}$ was reached, and for 2a-7, 2a-8 and 2b-1 with stoichiometries of hydrosilane–methoxysilane of 0.95/1 and 0.975/1, respectively, using the pre-polymer of $M_w \sim 580$ g mol$^{-1}$, where molecular weights of $M_w = 20 \text{,}600$ g mol$^{-1}$, $M_w = 22 \text{,}000$ g mol$^{-1}$ and $M_w = 22 \text{,}000$ g mol$^{-1}$ were achieved. Copolymers prepared with the $M_w \sim 1200$ g mol$^{-1}$ pre-polymer display polydispersity indexes ($M_w/M_n$) from 2.20 to 3.80, whereas copolymers prepared with the lower molecular weight pre-polymer of $M_w \sim 580$ g mol$^{-1}$ display $M_w/M_n$ in the range of 2.84 to 3.62.

**Table 1** SEC results for prepared functional siloxane copolymers with varying pendant groups as well as varying end-groups

<table>
<thead>
<tr>
<th>Entry</th>
<th>$M_w$ pre-polymer [g mol$^{-1}$]</th>
<th>Stoichiometry hydrosilane–methoxysilane</th>
<th>Functional group</th>
<th>End-group</th>
<th>$M_w \times 10^{-3}$ [g mol$^{-1}$]</th>
<th>$M_w/M_n$</th>
<th>Estimated value of $n$</th>
<th>Estimated value of $m$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>~1200</td>
<td>1/1</td>
<td>Chloro</td>
<td>Methoxy</td>
<td>50.4</td>
<td>2.22</td>
<td>15</td>
<td>34</td>
</tr>
<tr>
<td>2a-1</td>
<td>~1200</td>
<td>1/1</td>
<td>Chloro</td>
<td>Vinyl</td>
<td>47.9</td>
<td>2.20</td>
<td>15</td>
<td>34</td>
</tr>
<tr>
<td>2a-2</td>
<td>~1200</td>
<td>0.95/1</td>
<td>Chloro</td>
<td>Vinyl</td>
<td>70.3</td>
<td>2.03</td>
<td>15</td>
<td>49</td>
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<tr>
<td>2a-3</td>
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<td>Chloro</td>
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<td>15</td>
<td>49</td>
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<tr>
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<td>~1200</td>
<td>1/0.9</td>
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<td>3.23</td>
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<tr>
<td>2a-5</td>
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<td>1/0.8</td>
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<tr>
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<td>0.95/1</td>
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<tr>
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<td>Chloro</td>
<td>Vinyl</td>
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<td>27</td>
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<tr>
<td>2b-1</td>
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<td>0.95/1</td>
<td>Chloro</td>
<td>Alkyld</td>
<td>22.1</td>
<td>3.49</td>
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<tr>
<td>2a-9</td>
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<td>1/0.95</td>
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<td>32.7</td>
<td>4.30</td>
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</table>

**Scheme 2** Synthetic route for telechelic vinyl/allyl siloxane copolymers via borane catalysed polycondensation.

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End-functionalisation of 1 with vinyl- or allyldimethylsilane produced copolymers 2a and 2b, as seen in Scheme 2. These end-groups were chosen because they allow prepared copolymers to be used in the synthesis of silicone elastomers in platinum-catalysed hydrosilylation reactions. It is also possible to create copolymers with other end-groups, as long as the groups are compatible with the borane-catalysed reaction. Such end-groups, for example, could be, but are not limited to, silanes with aliphatics such as trimethyl-groups, aromatics and halogen-containing compounds. The prepared telechelic vinyl/allyl copolymers were characterised by FTIR spectroscopy, $^1$H- and $^{13}$C-NMR spectroscopy and SEC. The end-group conversion was investigated by NMR using low molecular weight copolymers, i.e. 2-a5, 2a-7 and 2b-1. In this way it was ensured that the end-groups were clearly visible in the recorded spectra. For the telechelic vinyl copolymers (2a) $^1$H- and $^{13}$C-NMR confirmed the reaction through the disappearance of the O−CH$_2$ protons and a carbon atom at $\delta_1$ = 3.49 ppm and $\delta_C$ = 49.9 ppm, respectively. The allyl-groups were detected by $^1$H-NMR as resonances at $\delta_1$ = 1.5 ppm (−CH$_2$−CH=CH$_2$), $\delta_H$ = 4.86−4.92 ppm (−CH=CH$_2$) and $\delta_1$ = 5.79 ppm (−CH=CH$_2$) and by $^{13}$C-NMR as resonances at $\delta_C$ = 26.4 ppm (−CH$_2$−CH=CH$_2$), $\delta_C$ = 113.7 ppm (−CH=CH$_2$) and 133.8 ppm (−CH=CH$_2$).

Converting the methoxy end-groups to vinyl/allyl end-groups did not alter the molecular weight of the copolymers, as illustrated in the SEC traces presented in Fig. 1. This also indicates that no unintended hydrosilylation reactions between the end-groups and vinyl- or allyldimethylsilane occur.

The synthesised chloro-functional copolymers were converted to azido-functional (3) through nucleophilic substitution in THF, using tetrabutylammonium azide as a phase-transfer catalyst as seen in Scheme 3. Entry 2b-1 was selected for this purpose, as the obtained molecular weight of $M_w$ = 22 100 g mol$^{-1}$ lies within the desired range for use in elastomer synthesis. The copolymer was successfully converted from chloro- to azido-functional, and this reaction was followed by FTIR through the appearance of the distinctive −N$_3$ band at 2095 cm$^{-1}$. Furthermore, $^1$H- and $^{13}$C-NMR corroborated this through a shift in the resonance signals of CH$_2$−Cl ($\delta_1$ = 3.50 ppm, $\delta_C$ = 47.6 ppm) to CH$_2$−N$_3$ ($\delta_1$ = 3.23 ppm, $\delta_C$ = 54.1 ppm). The prepared azido-functional copolymer was characterised by SEC, the results for which are shown in Fig. 2. It is evident that the molecular weight after the azide-substitution reaction is lower than for the corresponding chloro-functional copolymer, which could indicate that degradation has taken place. However, upon examination of the SEC overlays seen in Fig. 2, it is clear that no degradation has taken place, as both chromatograms are broad yet monomodal, with no lower molecular weight fragments appearing at higher elution volumes.

The lower obtained $M_w$ for the azido-functional copolymer must be ascribed to tailing and a shift in the baseline due to enhanced interactions of the latter with the SEC columns.
Functional dimethylsiloxane copolymers were created through a reaction with alkyne-functional molecules using CuAAC. Two different alkyne-containing molecules were chosen, in order to illustrate the versatility of the reaction. An aliphatic ATRP initiator and an alkyne-functional nitrobenzene were utilised as seen in Scheme 3. The ATRP initiator can be used to create polysiloxanes with different polymer side chains, whereas the aromatic compound 4-nitrobenzene can be used to increase dielectric permittivity in dielectric silicone elastomers.32 Click-functionalised copolymers were prepared under similar reaction conditions by means of a CuI-Et₃N catalytic system. The reaction products were characterised by FTIR spectroscopy, ¹H- and ¹³C-NMR spectroscopy and SEC. FTIR was used to confirm the completion of the click reaction through the disappearances of the alkyne and azide bands at ~3300 cm⁻¹ and ~2095 cm⁻¹, respectively. For the reaction with the ATRP initiator (4), which produced a green-brown polymer, a distinct ester C=O band at 1740 cm⁻¹ confirmed the presence of the 2-bromoisobutyrate group. In 5 the presence of 4-nitrobenzene was indicated by the red colour of the obtained polymer confirmed by bands at ~1605 cm⁻¹ for the aromatic C=C bonds and at ~1520 cm⁻¹ and ~1340 cm⁻¹ for the N=O bonds. FTIR spectra of 3, 4 and 5 can be seen in Fig. 3. The formation of the click products was furthermore confirmed by the presence of the triazole protons in ¹H-NMR, which appear at δ₄ = 7.61 ppm and δ₅ = 7.90 ppm for 4 and 5, respectively. An assigned representative ¹H-NMR spectrum of 4 can be found in the ESI.†

The SEC results for click-products 4 and 5 can be seen in Table 1 and Fig. 2. For both click-products higher molecular weights are obtained, and a slight shift towards higher molecular weight regions can be seen in the SEC traces, pointing to the successful attachment of functional groups onto the copolymers. Furthermore, SEC showed that 5 had a strong UV signal, unlike the starting materials 2b-1 and 3, which proves the attachment of the 4-nitrobenzene chromophore.

Ionic polymers are a rapidly expanding class of materials with interesting and promising properties39–41 which have recently been extended to silicone materials.42 Thus, as an example of another possible post polymerisation modification, the prepared chloro-functional copolymer 2a-8 was used in a substitution reaction with 1-ethylimidazole to form the ionic copolymer seen in Scheme 4. This reaction was followed by ¹H-NMR through a shift in the resonance of CH₂−Cl (δ₄ = 3.50 ppm) to CH₂−N⁺ (δ₄ = 4.43 ppm). After the reaction, the orange-brown copolymer was less soluble in toluene, thereby demonstrating the increased ionic/polar nature of the copolymer 6. The SEC results for the chloro-functional copolymer 2a-8 and imidazolium-functional copolymer 6 can be seen in Table 1 and Fig. 4. As observed for the click-products, a slight shift towards the higher molecular region is seen in the SEC traces for copolymer 6, which indicates the successful attachment of the functional group.

The prepared chloro- and azido-functional siloxane copolymers have great potential in the preparation of functional silicone elastomers where the properties of the elastomers can be altered and improved according to the given application and the type of group attached to the copolymer. The specific functional groups could include many different types32 and are not limited to those used in this study. We are currently investi-
gating the use of synthesised functional copolymers for the preparation of functional elastomers, thus elucidating their properties.

Conclusions

In conclusion, we have successfully synthesised telechelic vinyl/allyl chloro-, azido- and CuAAC-functionalised siloxane copolymers and ensured spatial control over the functional groups. The polycondensation reaction proved to be rapid and very robust, with high yields obtained. The method therefore offers a fast and reliable technique for the synthesis of structured functional polysiloxanes. The content of functional groups in the copolymers could be varied by changing the molecular weight of the hydride-terminated dimethyldiisoxane pre-polymers used in the polycondensation reactions. Furthermore, the molecular weights of the copolymers could be tuned by varying the stoichiometry of the hydrosilane and methoxy-silane starting materials. Polymers with any conceivable concentration of functionality and molecular weight can thereby be obtained.

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Notes and references

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