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**PAPER**

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## Synthesis of network polymers composed of well-defined silyl ether macrocycles

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We report a straightforward synthetic route to silyl ether-based network polymers, enabled by efficient macrocyclization of diols with dichlorosilacyclobutane (DCSB) followed by thermal ring-opening of the silacyclobutane units. This strategy allows well-defined macrocyclic motifs composed of silyl ether linkages to be embedded directly into the polymer backbone. The resulting films are optically transparent and exhibit excellent thermal stability. Mechanical characterization reveals relatively low hardness, reflecting the intrinsic flexibility of the silyl ether framework. Despite the hydrolytic sensitivity of the macrocyclic precursors, the resulting network films demonstrate high acid resistance, which is attributed to their hydrophobic surface properties.

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Silyl ether-based polymers (SEPs) have gained considerable interest due to their fascinating properties distinct with conventional hydrocarbon materials, such as excellent thermal stability, flexibility, and optical transparency.<sup>1</sup> Consequently, SEPs have found various applications including elastomers, thermosets, and other advanced polymer materials.<sup>2–4</sup> Furthermore, although the Si–O bond is generally prone to hydrolysis and alcoholysis, such a labile nature of the Si–O bonds has been utilized for the development of degradable polymer and vitrimer with dynamic covalent networks.<sup>5–13</sup> In addition to these advantageous features, the development of robust synthetic methodologies has greatly advanced SEP chemistry. Traditionally, SEPs have been synthesized by polycondensation of diols with dichlorosilanes, diaminosilanes, or dialkoxysilanes.<sup>14,15</sup> More recently, hydrosilylation of bis(carbonyl) comonomers has emerged as a powerful alternative route.<sup>16</sup> In addition, new strategies have been continuously established to expand the structural diversity and tunability of SEPs.

Dichlorosilacyclobutane is a commercially available silyl building block that possesses a distinctive dual and orthogonal reactivity. The Si–Cl groups readily undergo nucleophilic substitution to generate silyl ether linkages, whereas the silacy-

clobutane ring can undergo ring-opening reactions under thermal, photochemical, and catalytic conditions without compromising the integrity of the newly formed Si–O bonds.<sup>17–22</sup> Combination of these independent reactivity modes provides a promising platform for the construction of unprecedented polymer architectures. However, silyl ethers derived from silacyclobutanes are generally highly susceptible to hydrolysis, necessitating handling under inert atmosphere. Consequently, to take advantage of the dual reactivity of dichlorosilacyclobutane for the synthesis of SEPs, there is a strong need for a highly efficient synthetic method without any complicated experimental operation like column purification.

Previously, we reported an efficient macrocyclization that provides silyl ether-based macrocycles from readily accessible diols and dichlorodimethylsilanes.<sup>23</sup> In general, macrocyclization reactions suffer from intrinsic challenges, including the requirement for extremely dilute conditions (typically in the millimolar range) and inherently low macrocyclization efficiencies.<sup>24–26</sup> In contrast, our method achieves remarkably high efficiency and selectivity, affording macrocycles featuring silyl ether units at the vertices. Building upon this macrocyclization strategy, we now present a facile and efficient synthetic approach for producing novel silyl ether-based polymer networks composed of well-defined macrocyclic units. The method involves macrocyclization of diols with dichlorosilacyclobutane through Si–O bond formation, followed by thermal ring-opening of the silacyclobutane moieties to produce a densely crosslinked network polymer in which discrete macrocyclic structures are preserved (Fig. 1). The preparation of polymer films and their bulk properties are also described.

Our study began with syntheses of macrocyclic compounds using 4,4'-dihydroxybiphenyl (**1**) and [1,1'-bi(cyclohexane)]-4,4'-

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**Fig. 1** The synthetic strategy for silyl ether-based network polymer consisting of well-defined macrocyclic structures.

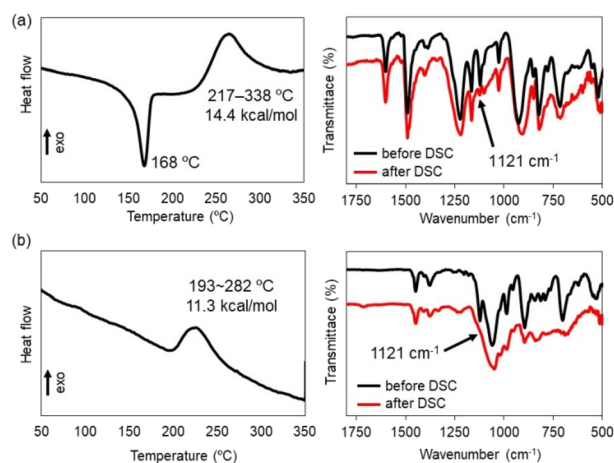
diol (**3**) as a linker (Scheme 1). Following the previously reported method, dichlorosilacyclobutane was treated with dihydroxybiphenyl in the presence of imidazole. The reaction afforded the desired product along with small amount of byproduct. After washing the crude product by acetonitrile, an analytically pure macrocycle was obtained in 90% yield.  $^1\text{H}$ ,  $^{13}\text{C}$ , and  $^{29}\text{Si}$  NMR spectroscopic analyses and mass spectrometry supported the formation of macrocycle **2** with exclusive selectivity. A rapid and efficient synthesis was also achieved when used with diol **3**. In this case, the starting diol was hardly dissolved in THF, while the reaction efficiently proceeded to provide soluble macrocyclic compound **4** almost



**Scheme 1** Macrocyclizations of diols with dichlorosilacyclobutane to provide macrocycles **2** and **4**.

quantitatively. The structure was further examined by single-crystal X-ray diffraction. Although the crystal quality was insufficient for full structural refinement (see SI), the analysis indicated that macrocycle **4** consists of four silacyclobutane units and four bicyclohexylene linkers, adopting an approximately square-shaped geometry in the solid state. This structural motif closely resembles that of the macrocycles reported in our previous work, whereas the conformations of the silyl ether units show slight variations that reflect their inherent flexibility.

Polymerization *via* the ring-opening reaction of the silacyclobutane units was first assessed by thermogravimetric analyses (TGA) and differential scanning calorimetry (DSC). As shown in Fig. 2a, macrocycle **2** exhibited melting point at 168 °C and subsequently an exothermic peak ranging from 217 °C to 338 °C. The exothermic peak was no longer observed upon reheating the sample. After heating over the observed exothermic peak, the sample became insoluble in common organic solvents. Fourier transform infrared (FTIR) spectroscopy indicated that, upon heating, a characteristic peak at 1121  $\text{cm}^{-1}$  assigned to the silacyclobutane ring significantly decreased.<sup>17</sup> These observations implied that a polymeric structure was formed *via* ring-opening reaction of the silacyclobutane units. We have already reported that macrocycle **5** bearing  $\text{Me}_2\text{Si}$  units instead of silacyclobutane unit at the vertices exhibited high thermal stability within 300 °C (Fig. 3). Furthermore, the peak of the reference compound **5** at around the characteristic peak of the silacyclobutane unit in the FT-IR spectrum remained essentially unchanged (see the SI). On the basis of these results, we concluded that the macrocyclic skeleton is maintained during the ring-opening reaction of the silacyclobutane unit. Note that other peaks particularly derived from linker units hardly changed upon the ring-opening reaction. This result also supported retention of the macrocyclic skeleton during the ring-opening reaction. Macrocycle **4** showed a similar thermal response (Fig. 2b). Although the



**Fig. 2** DSC analyses and FT-IR spectra of macrocycle **2** (a) and **4** (b). FT-IR analyses were performed by using the samples used in TGA analyses.







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