

# Chain-Growth Sulfur(VI) Fluoride Exchange Polycondensation: Molecular Weight Control and Synthesis of Degradable Polysulfates

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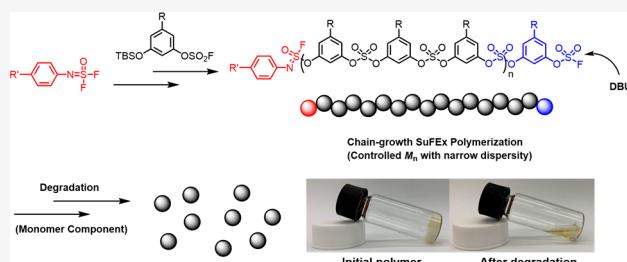
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**ABSTRACT:** Sulfur(VI) fluoride exchange (SuFEx) click chemistry has offered a facile and reliable approach to produce polysulfates and polysulfonates. However, the current SuFEx polymerization methods lack precise control of target molecular weight and dispersity. Herein, we report the first chain-growth SuFEx polycondensation process by exploiting the unique reactivity and selectivity of S–F bonds under SuFEx catalysis. Given the higher reactivity of iminosulfur oxydifluoride versus fluorosulfate, the chain-growth SuFEx polycondensation is realized by using an iminosulfur oxydifluoride-containing compound as the reactive chain initiator and deactivated AB-type aryl silyl ether-fluorosulfates bearing an electron-withdrawing group as monomers. When 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) was utilized as the polymerization catalyst, precise control over the polymer molecular weight and polydispersity was achieved. The resulting polymers possess great thermal stability but are easily degradable under mild acidic and basic conditions.



## INTRODUCTION

Since the modern concept of the polymer was introduced by Staudinger in the 1920s,<sup>1,2</sup> many polymers and polymerization methods have been developed to meet the needs of diverse applications. There are two main streams of polymerization approaches, namely, step-growth and chain-growth polymerization. In early days, Carothers established step-growth polymerization (polycondensation)<sup>3,4</sup> and led an aggressive expansion of synthetic polymers based on organic reactions.<sup>5,6</sup> However, the molecular weight of polymers is difficult to control in a step-growth polymerization process since the coupling occurs between monomers and oligomeric intermediates without any selectivity. In other words, step-growth polymerization lacks selectivity between initiation and the propagation process, leading to a broad molecular weight distribution.

In this respect, “chain-growth polycondensation” has attracted much attention from the polymer community. Since chain-growth polycondensation of polyamides<sup>7–9</sup> developed by Yokozawa in 2000, various polymers such as polyethers,<sup>10–12</sup> polyesters,<sup>13</sup> poly(ether sulfone)s,<sup>14</sup> and polythiophenes<sup>15</sup> have been synthesized in a controlled manner. However, most of these cases resulted in oligomers with molecular weights below 10.0 k despite their controlled manner.<sup>16–19</sup> Recently, many improved examples have been reported producing polyamides,<sup>20</sup> polythiophene,<sup>21</sup> poly(*p*-phenylene),<sup>22</sup> graphene nanoribbons,<sup>23</sup> as well as supramolecular polymers.<sup>24</sup>

An efficient coupling reaction is crucial for successful polymerization to produce well-defined and high-molecular-weight polymers. We and others have explored the benefits of the best click chemistry reactions in polymer synthesis; such reactions enable complete conversion along with unique orthogonal reactivity toward various functional groups. Cu-catalyzed azide alkyne cycloaddition (CuAAC), a prototype of “click” chemistry creating 1,4-triazole connections, has served with great reliability to produce stable, covalent triazole attachment points into various functional polymers<sup>25</sup> and materials<sup>26–28</sup> with high regioregularity. Moreover, complex structures<sup>29–31</sup> and higher architectures such as graft and dendronized polymers<sup>32</sup> were also successfully synthesized by using its advanced version (Cu-catalyzed multicomponent polymerization). Most of the examples afforded diverse step-growth polymers, while there are few reports of chain-growth type CuAAC polymerization by holding Cu catalysts at the end of the growing chain.<sup>33,34</sup>

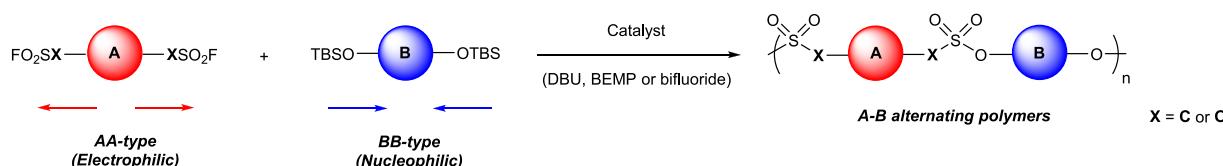
With another recent click-caliber reaction, SuFEx [sulfur(VI) fluoride exchange], it is now possible to create stable sulfate and sulfonate links with great ease and reliability.<sup>35,36</sup> Via this approach, we have synthesized polysulfates and

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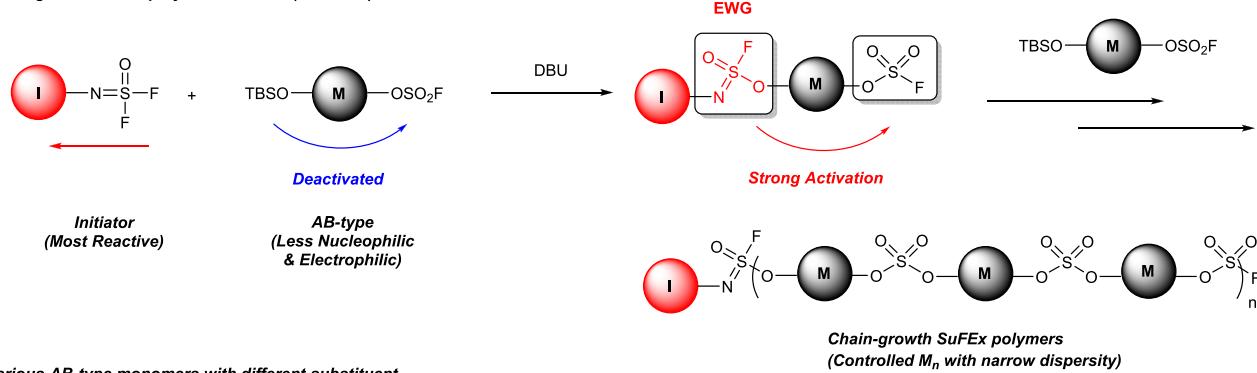
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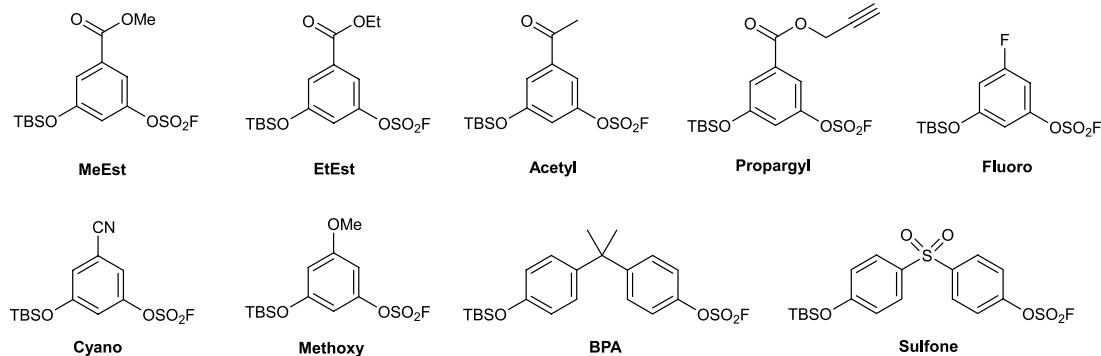
## a. Step-growth SuFEx polymerization (previous)



## b. Chain-growth SuFEx polycondensation (this work)



## c. Various AB-type monomers with different substituent



**Figure 1.** Schematic procedure of SuFEx polymerization. (a) Conventional step-growth polycondensation. (b) Chain-growth SuFEx polycondensation. (c) Various AB-type monomers with different electronics.

polysulfonates,<sup>37–39</sup> in which AA- and BB-type monomers are used as building blocks (Figure 1a), and the polymerization takes place between the fluorosulfate and the silyl ether-bearing monomers in the presence of catalysts such as 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) and 2-*tert*-butylimino-2-diethylamino-1,3-dimethyl perhydro-1,3,2-diazaphosphorine (BEMP). In terms of electronic properties, such a polymerization process can be depicted as a coupling reaction between an electrophilic monomer (fluorosulfates) and a nucleophilic counterpart (silyl ethers).

The intriguing observation was that the resulting polymers had somewhat moderate molecular weight distribution regardless of the step-growth design.<sup>40</sup> To date, a controlled chain-growth type polymerization enabled by SuFEx has yet to be developed. Here, we report the first chain-growth SuFEx polycondensation by modifying the electronic properties of SuFEx-able monomers to achieve precise control of the high molecular weight of polysulfates with narrow dispersity. Moreover, the resulting polymers were fully degradable under mild acidic and basic conditions.

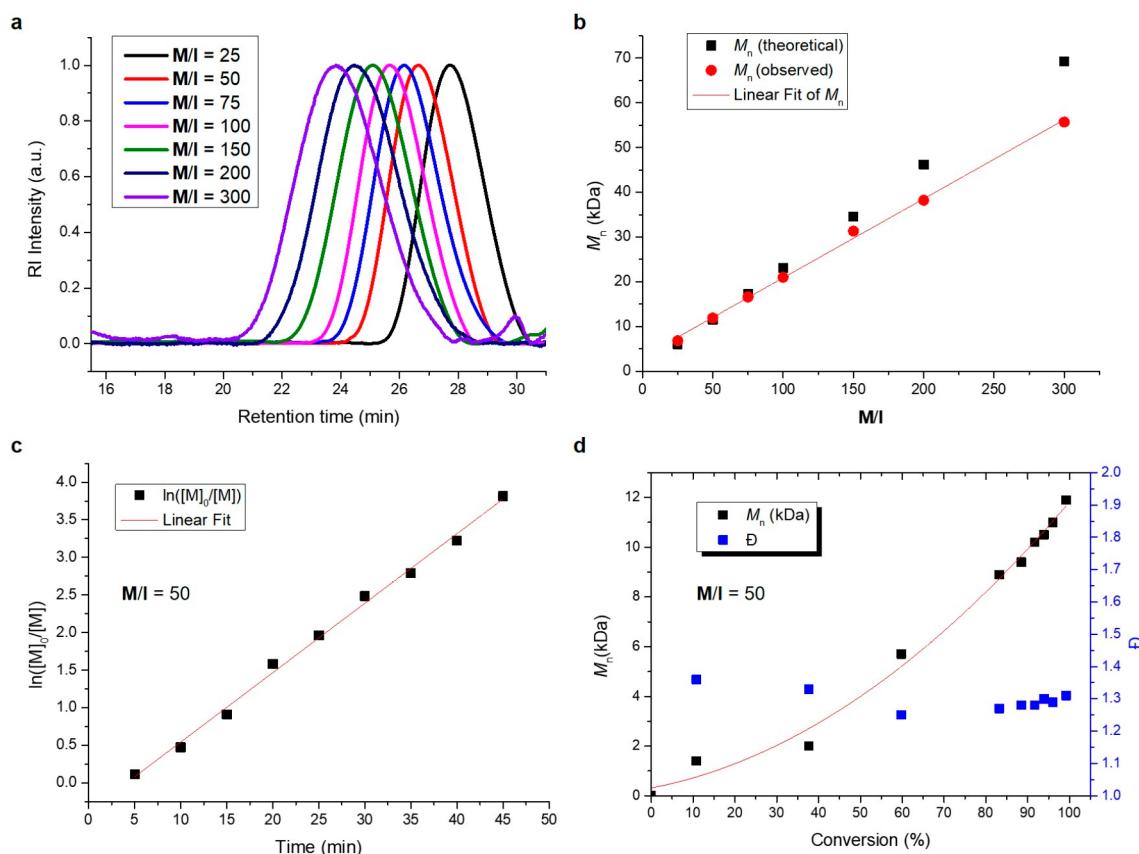
## RESULTS AND DISCUSSION

### Monomer Design and Evaluation of Chain-Growth Polycondensation.

To develop a SuFEx-based chain-growth polymerization requires: (1) A SuFExable initiator with significantly higher reactivities than monomeric building blocks, and (2) monomers that can undergo chain propagation.

Previously, we discovered that the reactivity of various S–F bonds for SuFEx follows the order of  $-\text{N}=\text{SOF}_2 \gg -\text{SO}_2\text{F} > -\text{OSO}_2\text{F}$ .<sup>41</sup> Therefore, iminosulfur oxydifluoride seems to be a reasonable choice as the initiator for our proposed polymerization. To realize chain-growth polycondensation, AB-type monomers in a conjugated aromatic system that harbors a nucleophilic (-OTBS) group and an electrophilic group (-OSO<sub>2</sub>F) will be employed. Importantly, the electronic properties of such a monomer can be fine-tuned such that the -OSO<sub>2</sub>F group would not react with the -OTBS group within the same monomer but would react with the -OTBS group of another monomer to initiate the chain propagation once the polymerization is initiated (Figure 1b).

To test our hypothesis, a panel of AB-type monomers was synthesized as 1,3,5-trisubstituted monomers (Figure 1c). An electron-withdrawing group (EWG) or an electron-donating



**Figure 2.** Molecular weight control of model polymerization with AB-type monomer (MeEst) and kinetic profiles. (a) SEC traces of various monomer-to-initiator ratios (M/I). (b)  $M_n$  vs M/I correlation. (c) First-order kinetics of SuFEx polymerization at a fixed M/I ratio of 50. (d)  $M_n$  vs conversion and  $D$  ( $M_w/M_n$ ) vs conversion correlation at a fixed M/I ratio of 50.

group (EDG) was introduced to the meta- or para-position of both electrophilic and nucleophilic sites to tune the properties of the resulting monomers.

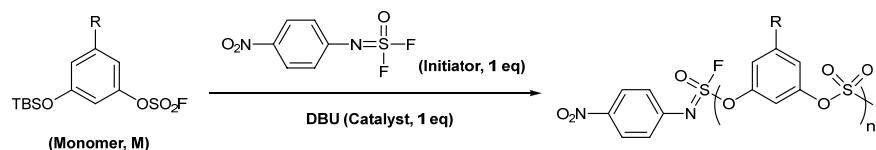
In the absence of any initiators, Methoxy and BPA monomers underwent self-condensation under our previously established SuFEx polymerization condition (20 mol % of DBU).<sup>35</sup> By contrast, under the same condition, the monomers bearing EWG (MeEst, EtEst, Acetyl, and Fluoro) did not produce any polymers. Presumably, the presence of two EWGs (i.e., electron-poor substituent (-R) and fluorosulfate) inductively weakens the nucleophilicity of phenol,<sup>42,43</sup> impeding effective SuFEx coupling.

Interestingly, although electron-poor monomers did not produce self-condensation polymers, they successfully polymerized in the presence of an iminosulfur oxydifluoride (-N=SOF<sub>2</sub>) initiator (I) that also contains a 4-nitrobenzene group. A dry nitrile-based solvent, butyronitrile, rather than hygroscopic solvents such as DMF and NMP, ensured the reproducibility of polymers at high temperatures (Table S1, entries 7–13).

**Kinetic Studies and Molecular Weight Control of a Model Polymerization.** With a fixed monomer-to-initiator ratio (M/I) of 50, we then performed kinetic studies with a model polymerization of MeEst and the active initiator (I) to determine if a controlled chain-growth-type polymerization is realized. After polymerization started, we observed a full conversion of the initiator into the chain-end taking place within 3 min (see <sup>1</sup>H and <sup>19</sup>F NMR spectra in Figure S3). By analyzing aliquots taken at varying time intervals, we found

that the consumption of MeEst exhibited first-order kinetics (Figure 2c) and the molecular weight of the polymer increased in proportion to the conversion. The observed initiation rate ( $k_i = 21.9 \times 10^{-3} \text{ s}^{-1}$ ) is much faster than the propagation rate ( $k_p = 1.0 \times 10^{-3} \text{ s}^{-1}$ ), and the high  $k_i/k_p$  ratio is expected to promote the controlled polymerization. Importantly, the molecular weight distribution maintained approximately 1.3 even at an overall conversion of 100% (Figure 2d), indicating that this polymerization process does not follow a typical step-growth polymerization, which normally affords a broad distribution over 2.0 at the full conversion.

We further conducted a detailed survey of how the molecular weight of MeEst polymers would be controlled at various M/I ratios (Table 1). As an optimized condition, the initiator to DBU ratio (I/cat.) was set to 1:1 to get reasonable kinetics of polymerization (Table 1, entry 2). When all monomers were consumed, the resulting polymers exhibited unimodal and low distributions as analyzed by size-exclusion chromatography (SEC) using polystyrene standards (Figure 2a). Varying the ratios of monomer to initiator from 25 to 300, the observed number-average molecular weight ( $M_n$ ) of the polymers showed a linear increase (Figure 2b). In addition, the degree of polymerization observed by the end-group analysis matched the feeding ratio (Figure S2). The dispersity ( $D = M_w/M_n$ ) of the MeEst polymer remained at 1.3 until the M/I ratio increased to 100 (Table 1, entries 1, 2, 5, and 6). However, when the M/I reached 150, broadening was observed (Table 1, entry 7).

Table 1. SuFEx Polymerization of Various AB-type Monomers with Active Initiator (I)<sup>a</sup>

entry <sup>a</sup>	monomer	targeted DP (observed) <sup>b</sup>	[M]:[I]:[Cat.]	temp (°C)	time (h)	conv <sup>c</sup> (%)	$M_{n,\text{theo}}^d$	$M_{n,\text{SEC}}^e$	$D^e$
1	MeEst	25	25:1:1	90	0.3	99	6.0 k	6.8 k	1.27
2	MeEst	50 (52)	50:1:1	90	1	99	11.5 k	11.9 k	1.28
3	MeEst	50	50:1:0.5	90	3	99	11.5 k	12.8 k	1.30
4	MeEst	50	50:1:0.2	90	12	99	11.5 k	10.9 k	1.26
5	MeEst	75	75:1:1	90	2	99	17.3 k	16.6 k	1.37
6	MeEst	100	100:1:1	110	2	99	23.1 k	21.0 k	1.35
7	MeEst	150	150:1:1	110	8	99	34.6 k	31.3 k	1.45
8 <sup>f</sup>	MeEst	200	200:1:1	110	48	>95	46.2 k	38.2 k	1.44
9 <sup>f</sup>	MeEst	300	300:1:1	110	72	>95	69.3 k	55.7 k	1.55
10	EtEst	50 (49)	50:1:1	90	1	99	12.4 k	12.2 k	1.29
11	EtEst	100	100:1:1	110	3	99	24.6 k	23.8 k	1.29
12 <sup>f</sup>	EtEst	200	200:1:1	110	48	99	49.0 k	39.5 k	1.39
13 <sup>f</sup>	EtEst	300	300:1:1	110	72	99	73.5 k	66.6 k	1.46
14	Acetyl	50 (50)	50:1:1	90	1	99	10.7 k	13.2 k	1.27
15	Acetyl	75	75:1:1	90	2	99	16.1 k	16.8 k	1.25
16	Acetyl	100	100:1:1	90	2	99	21.5 k	20.4 k	1.29
17	Acetyl	150	150:1:1	90	8	99	32.2 k	28.3 k	1.31
18 <sup>f</sup>	Acetyl	200	200:1:1	90	48	>95	43.0 k	42.6 k	1.43
19 <sup>f</sup>	Acetyl	300	300:1:1	90	72	>95	64.5 k	53.0 k	1.52
20	Fluoro	50 (56)	50:1:1	90	1	99	9.5 k	9.7 k	1.31
21	Fluoro	75	75:1:1	90	2	99	14.3 k	14.0 k	1.37
22	Cyano	50	50:1:1	90	1	99	10.1 k	insoluble	
23	Sulfone	25	25:1:1	90	4	99	8.0 k	17.6 k	1.31
24	Sulfone	50 (78)	50:1:1	90	12	99	15.6 k	31.0 k	1.18

<sup>a</sup>Polymerization was conducted on a 0.5 mmol scale. <sup>b</sup>Degree of polymerization (DP) was determined by end-group analysis of <sup>1</sup>H or <sup>19</sup>F NMR of polymer. <sup>c</sup>Conversions were determined by <sup>1</sup>H and <sup>19</sup>F NMR of the crude mixture. <sup>d</sup> $M_{n,\text{theo}} = \text{MW(I)} + \text{M/I ratio} \times \text{MW(M)}$ . <sup>e</sup>Determined by THF SEC calibrated using PS standards.  $M_n$  is given in g/mol. <sup>f</sup>Premixed stock solution (initiator + DBU) was applied to initiate polymerization.

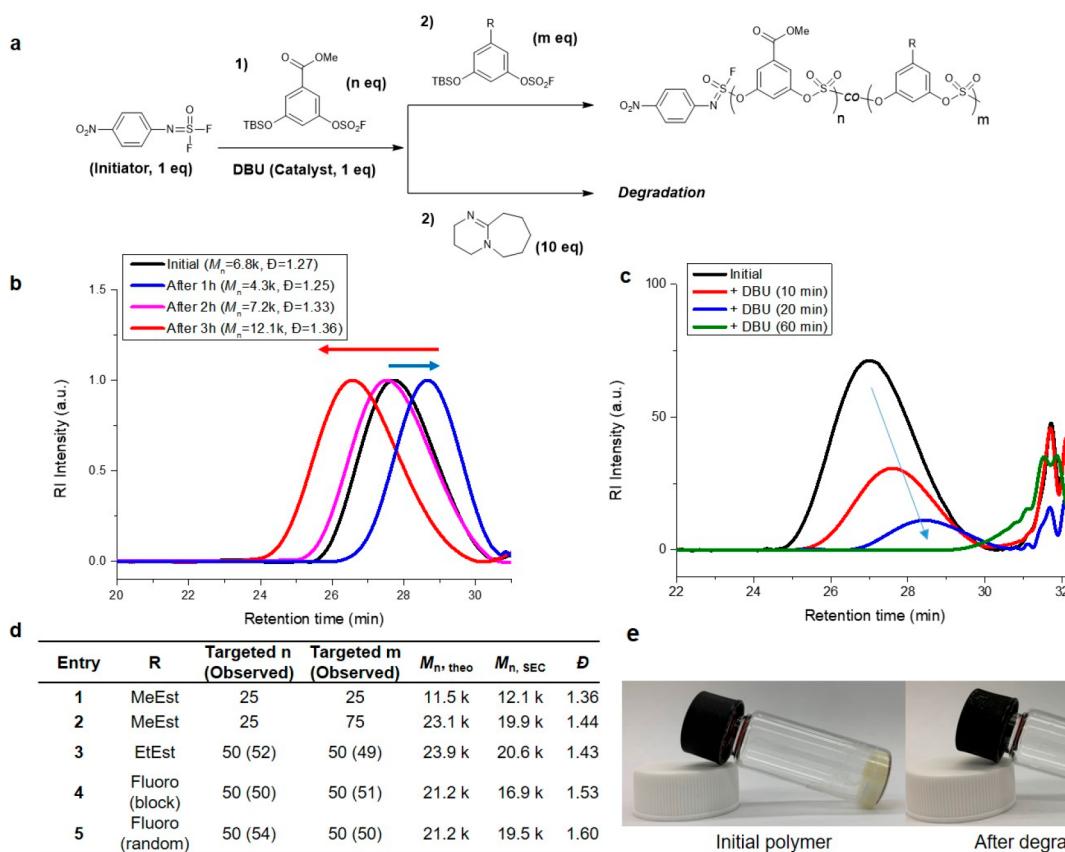
To make polymers with higher monomer-to-initiator ratios (M/I = 200 and 300), a premixed stock solution of the initiator and DBU was applied to achieve a fast initiation in the presence of high concentrations of monomers (Figure S1). Under these conditions, the  $D$  values of 1.44 and 1.55 were achieved for polymer products with the M/I of 200 and 300, respectively (Table 1, entries 8 and 9). The observed broadening may be caused by the chain-end decomposition ( $k_t$ ) during the long reaction course and the slower propagation rate ( $k_p$ ) by the excess of monomer that hinders proper coupling via DBU catalysis on the growing chain-end.

**Expansion of Substrate Scope with Various AB-type Monomers.** Building upon the above results, we explored various AB-type monomers to expand the substrate scope for chain-growth SuFEx polycondensation. The EtEst monomer, which has more hydrolytic resistance than MeEst, was examined for the polymerization. The molecular weights of the resulting polymers were in good agreement with calculated values at M/I ratios of 50–300, showing a  $D$  range of 1.29–1.46 (Table 1, entries 10–13). Similar trends were observed when using a better  $\pi$ -accepting Acetyl monomer (Table 1, entries 14–17). Not surprisingly, the resulting polymers at high M/I ratios (200 and 300) also had slightly broader distributions (Table 1, entries 18 and 19).

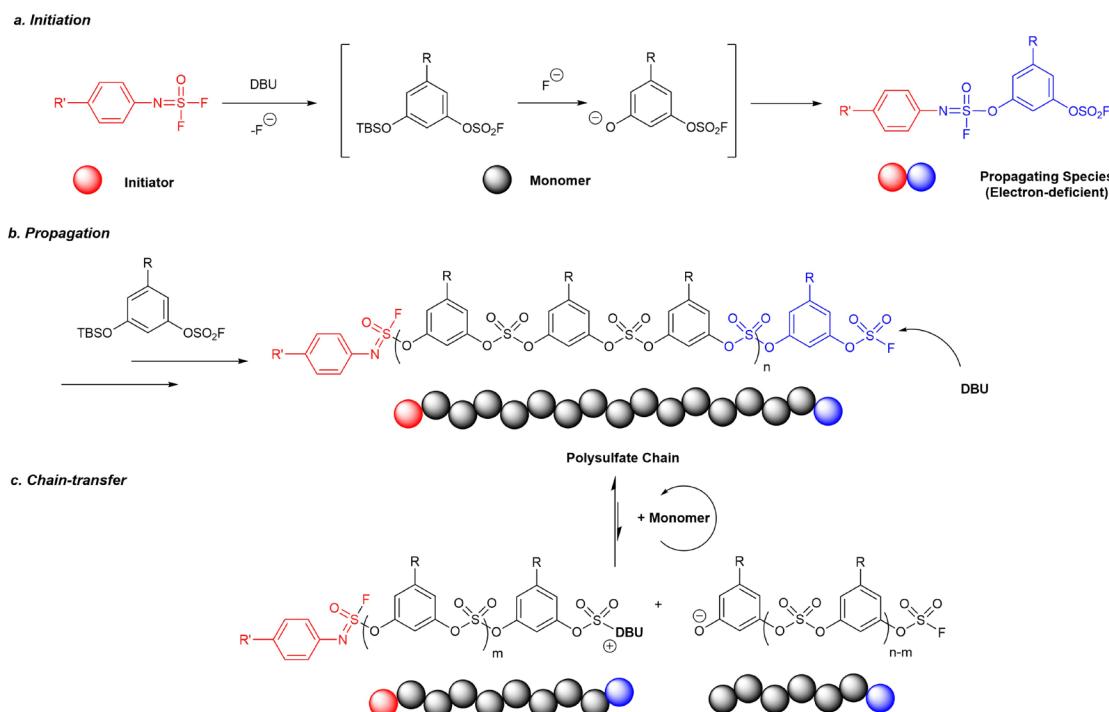
The monomers with other electron-withdrawing groups polymerized as well, showing a similar narrow dispersity

(Table 1, entries 20–24). However, these monomers have a limitation in high M/I ratios due to a lack of solubility. The Fluoro monomer could grow to M/I of 50 and 75, and the Sulfone derivative had an M/I of 25 and 50 as a maximum feeding ratio. Unexpectedly, the Cyano derivative crashed out during the polymerization and produced an insoluble solid in various organic solvents (Table 1, entries 22). Among these monomers, the most electron-deficient sulfone analogue showed the narrowest  $D$  value (1.18), implying a well-controlled behavior in polymerization (Table 1, entry 24).

**Chain-Extension Studies with Combination of AB-type Monomers.** Next, we conducted chain-extension experiments with various EWG analogues to further verify that our SuFEx polymerization proceeded via the chain-growth mechanism (Figure 3a). After the formation of the first block poly(MeEst)<sub>25</sub> ( $M_n = 6.8$  k,  $D = 1.27$ ), the end-group signal of -OSO<sub>2</sub>F remained at a low level (12%) after precipitation in methanol as observed in <sup>19</sup>F NMR (Figure S4), suggesting that the propagating chain-end is very reactive but also hygroscopic. We then reacted 25 or 75 equiv of additional MeEst monomer with the first block poly(MeEst)<sub>25</sub> for homoextension, and we observed that the pristine polymer successfully elongated with clear shifts in the SEC. Interestingly, the molecular weight of the initial polymer went down within 1 h upon the addition of the second monomer. It recovered to the original value shortly after and extended to the desired molecular weight after 3 h



**Figure 3.** Chain-extension (copolymerization) and degradation test of polysulfate. (a) Schematic procedure of sequential addition for copolymerization and degradation. (b) SEC traces of chain-extension of poly(MeEst)<sub>25</sub>. (c) SEC traces of poly(MeEst)<sub>50</sub> degradation with different time scales. (d) Various copolymerization results. (e) Images of poly(MeEst)<sub>50</sub> (Table 1, entry 2) before and after degradation.



**Figure 4.** A proposed mechanism of chain-growth SuFEx polycondensation. (a) Selective initiation of iminosulfur oxydifluoride to form a propagating dimer. (b) Propagation step by an iterative SuFEx reaction. (c) Chain-transfer reaction through activation of sulfate linkage by DBU.

(Figure 3b). However, the observed  $D$  of the extended polymer was found to be broader in comparison to the initial pristine polymer with  $M/I = 50$  (1.36 vs. 1.28) (Figure 3d, entry 1 vs Table 1, entry 2). This trend was similar to  $M/I = 25 + 75$  versus  $M/I = 100$  case (1.44 vs. 1.35) (Figure 3d, entry 2 vs Table 1, entry 6).

Combining other electron-poor monomers (EtEst and fluoro) with the first block poly(MeEst)<sub>50</sub> ( $M_n = 11.9$  k,  $D = 1.28$ ) also showed high-molecular-weight shifts in the SEC with relatively broader  $D$  values (Figure 3d entries 3, 4, and Figure S11). The broadness seemed to be induced by different propagation rates ( $k_p$ ) of the monomers (Figure S6) and the chain-transfer reaction. Of the catalysts that we studied, the chain-extension was only possible in the presence of DBU. Other catalysts (e.g., BEMP and bifluoride) resulted in no chain-extension of the initial polymers (Figure S11).

**Microstructure Analysis of Polysulfates from Block and Random Copolymerization.** To identify the microstructure of the chain-extended polymers, we also conducted thermal analysis of block and random copolymers from two distinct monomers. Since all the polysulfates except for the Fluoro homopolymer have an amorphous character without any melting transition or crystallization by differential scanning calorimetry (DSC), we chose copolymers formed by MeEst and Fluoro monomers for the detailed analysis (Table S5; cold crystallization temperature of Fluoro homopolymer: 69.2 °C and melting temperature: 146.7 °C). There were two glass transition temperatures ( $T_g$ ) appearing at 31 and 57 °C from the block copolymers formed from MeEst and Fluoro (Figure 3 entry 4). On the contrary, a random copolymer (Figure 3 entry 5) showed a single  $T_g$  at 30 °C. In addition, the intrinsic crystalline property of the Fluoro segment was expressed only in block copolymerization as  $T_c$  of 114.4 °C in the cooling cycle.

With the distinct patterns of the <sup>1</sup>H and <sup>19</sup>F NMR signal (Figure S7), all of the results indicate that block and random copolymerization produced different microstructures. Nonetheless, the block copolymerization runs in a block-like manner even though the second monomer has a chance of insertion into the first block by chain-transfer. All of these electron-deficient polysulfates exhibited great thermal stability as obtained by thermal gravimetric analysis (TGA). The decomposition temperatures ( $T_d$ ) of polysulfates ranged from 328.5 to 387.3 °C, and all the copolymers displayed a merged  $T_d$  of each homopolymer.

**Demonstration of Proposed Mechanism of Chain-Growth SuFEx Polycondensation.** The above results shed light on a possible mechanism of chain-growth SuFEx polycondensation. In the presence of an active initiator such as difluoride (I), DBU selectively activates the initiator over monomers (Figure 4a, initiation). The strong affinity of the exchanging fluoride for silicon generates phenoxide, and the substituent effect of 1,3,5-functionalized monomer is retained. Even though AB-type monomers bearing an EWG are deactivated for SuFEx polymerization, one SuFEx coupling with initiator could change the electronic properties of the monomer to the polymerizable state (i.e., electron-deficient dimer). This can be considered as an intramolecular transformation of the substituent from an electron-rich group (−OTBS) to an electron-poor group (−OS(O)(F)=NAr). Once changed, it allows a relay SuFEx coupling to be induced, leading to a continuous propagation in polymerization (Figure 4b, favorable pathway).

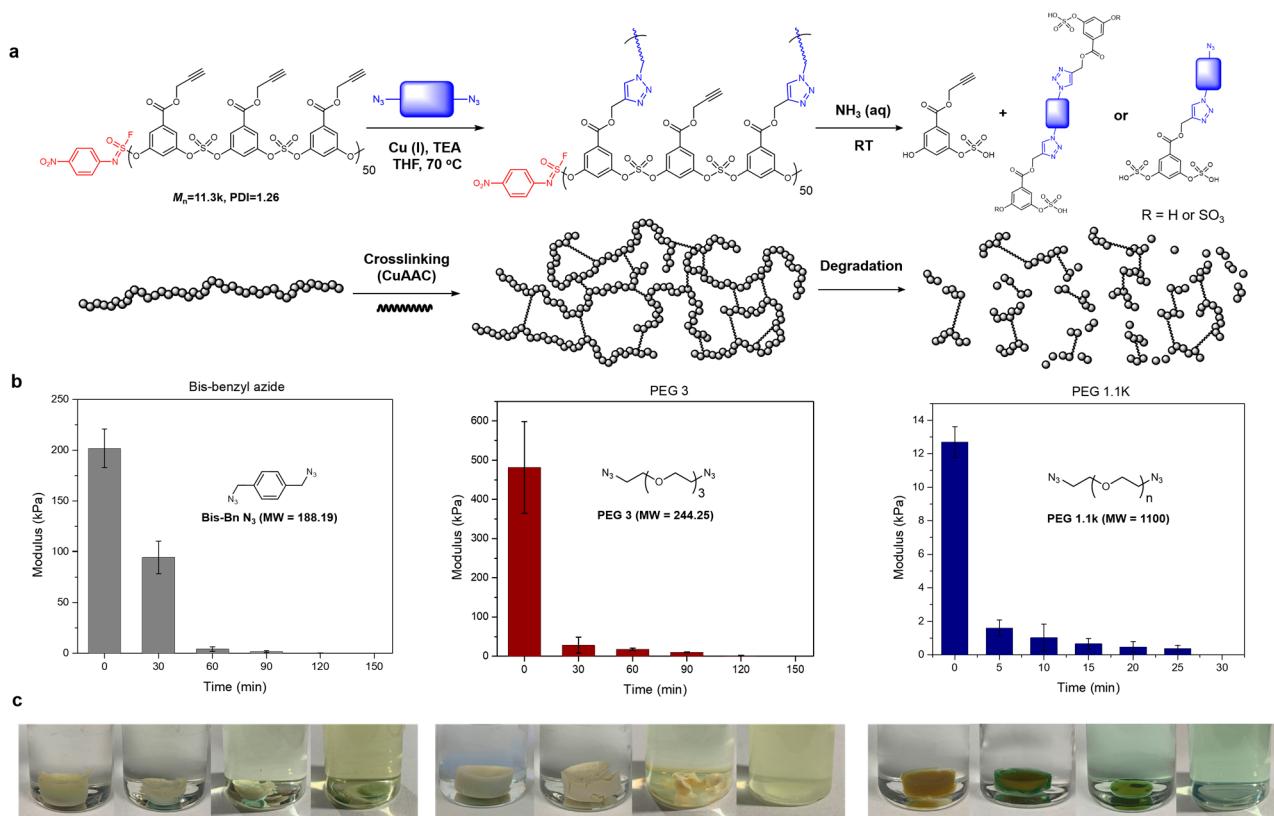
However, because the generated backbone is composed of electron-poor sulfate bonds, the propagation contains a chain-transfer reaction activated by DBU (Figure 4c). The bending feature in the  $M_n$  versus conversion plot implies that chain-transfer arises during the polymerization (Figure 2d). Despite the chain-transfer that can cause step-growth contaminants (see also Figure S5, MALDI-TOF), the substituent effect still influences propagation, and thus dispersity was not severely broadened like in typical step-growth polymerization.

As a chain-transfer reagent, we confirmed that a low loading of DBU proceeded to initiator-free polymerization in the case of  $M/I = 50$  and 100. We expected that polymerization occurred by forming bis-sulfate dimers in equilibrium. However, the molecular weight of the initiator-free polymerization was not well-regulated, showing a higher molecular weight than the case of MeEst polymerization at  $M/I = 50$  and a much broader distribution than the case of MeEst polymerization at  $M/I = 100$  (Figure S9). Therefore, building predictable amounts of the polymerizable dimer and the fast initiation ( $k_i$ ) from the high reactivity of initiators (I;  $-NSOF_2$  or I-1;  $-SO_2F$ ) is essential for controlling  $M_n$  and  $D$  values. Additionally, applying more active catalysts (e.g., BEMP and bifluoride) can give a different microstructure through activating the two fluorides of the initiator (Figure S10).

**Degradability of Polysulfate Backbone and Derived Cross-Linked Gels.** Degradable polymers are desirable for sustainability.<sup>44–47</sup> Although stable covalent linkages in conventional polymers have contributed to the development of practical materials with high strength and resistance, ironically, their durability and nonrecyclability due to the irreversible cross-linking, such as that found in thermosets, have become a major cause of plastic pollution nowadays. This emerging awareness has triggered a demand for degradability in polymeric materials.

To explore if our polysulfate polymers possess any degradability, we subjected the electron-deficient polysulfate [poly(MeEst)<sub>50</sub>] to various conditions (Table S3). Because the previous studies showed that polysulfonates and polysulfamides can be degraded by DBU (or base) at an elevated temperature,<sup>48,49</sup> we first tested the degradability of our polysulfates by incubating poly(MeEst)<sub>50</sub> with DBU (10 mol % in THF) at 90 °C. In a few minutes, the polymer changed from a solid to a liquid state (Figure 3c,e) and was completely degraded within 1 h. The polymer also can fully degrade at rt, but it takes a longer time (4 h). LC-MS analysis confirmed the presence of monosulfates, bis-sulfates, and trimer sulfates in the degraded solution (Figure S8). Notably, under the same condition, we did not observe the degradation of BPA polysulfate<sup>35</sup> (also see Table S4). This result suggested that the electron-deficient substituents on the polymer backbone weakens the sulfate bond (−SO<sub>4</sub><sup>2−</sup>) toward a nucleophilic base.

We then examined a few related catalysts such as 4-dimethylaminopyridine (DMAP) and 2-*tert*-butyl-1,1,3,3-tetramethylguanidine (BTMG). However, as a relatively weak pyridyl base, DMAP only led to partial polymer degradation even after 24 h exposure with heating. Although BTMG has similar basicity to DBU, it only started to induce degradation at elevated temperatures (Table S3, entry 7 and entry 9). Further studies conducted in various aqueous buffers revealed that this polymer was stable between pH 5 to pH 7 but sensitive toward mild acidic and basic conditions.<sup>50</sup> Both aqueous ammonia and 0.5 M KOH solution could lead to its full degradation.



**Figure 5.** Degradation of polysulfate cross-linking gel. (a) Formation and degradation of CuAAC cross-linking gels. (b) Degradation modulus in soaking aqueous ammonia. (c) Images of degrading gels at room temperature with different time intervals (see section 16 in Supporting Information for details).

With the properties of our polysulfate backbone characterized, we next investigated degradability of cross-linked gels formed by polysulfates. These gels, so-called, thermosets are known to be difficult to break and hard to remold due to their permanent cross-linking resulting in multiple 3D-network structures. Recently, many approaches to overcoming this issue have been reported by applying sensitive or reversible bonds toward various stimuli, such as acid,<sup>51</sup> base,<sup>52</sup> anion,<sup>53,54</sup> radical,<sup>55</sup> and dynamic bonds.<sup>56,57</sup>

To construct cross-linked gels, we prepared a polymer with the polysulfate backbone decorated with propargyl side chains (M/I = 50). We then used CuAAC to induce the cross-linking of the resulting polymer with different types of bis-azides to produce gel-like materials (Figure 5a). We tracked the moduli of each gel by the nanoindentation technique. Among three different cross-linkers, the rigid bis-benzyl and short PEG linker formed relatively stiff gels, showing a higher initial modulus (202 kPa for bis-benzyl azide and 482 kPa for PEG 3, respectively). As the spacer became longer, e.g., N<sub>3</sub>PEGxN<sub>3</sub> 1.1 k, a soft elastic gel was obtained with a lower Young's modulus (13 kPa) (Figure 5b).

To determine the degradability of the above cross-linked gels, we placed them in aqueous ammonia solution at room temperature and checked their status. As the gels hydrolyzed (Figure 5c), the solution gradually turned green by the chelation of ammonia with the trace amount of Cu species entrapped inside of the gels. The modulus of the rigid bis-benzyl azide gel fell by half within 30 min (202 to 94 kPa), and the gel turned gummy after 1 h. Because of the hydrophobic nature of the bis-benzyl spacer, a trace of the degraded residue remained as aggregates in aqueous solution; however, gels

cross-linked via the water-soluble polyethylene glycol (PEG) units afforded a transparent solution after degradation. Moreover, faster soaking and decomposition occurred when more hydrophilic spacers were used. For example, the gel cross-linked by the short PEG 3 spacer showed only severe cracking after 30 min (from 482 to 28 kPa), whereas the more hydrophilic PEG 1.1 k spacer showed a much faster decrease in modulus within 5 min (from 13 to 1.6 kPa), producing a clear solution after 25 min (see CuAAC gel section in Supporting Information for more information).

## CONCLUSION

In summary, we have developed the first chain-growth SuFEx polycondensation by exploiting the high reactivity of iminosulfur oxydifluorides over fluorosulfates. Introducing a selective initiator and AB-type monomers was the key to achieve successful chain-growth SuFEx polycondensation. To maximize the electronic effect, monomers were designed with a nucleophile (silyl ether), an electrophile (fluorosulfate), and an additional EWG. The substituent effect of various electron-deficient AB-type monomers separates the reactivity of fluorosulfate (-OSO<sub>2</sub>F) in the polymer chain-end from its counterpart in the monomer, providing polysulfates with well-controlled molecular weight and narrow dispersity.

However, since this SuFEx polymerization adopts a chain-transfer reaction, the sequential monomer addition results in a block-like structure, and increasing the amounts of DBU causes the degradation of polymer. As the susceptibility of the sulfate bonds is dependent on the electronic environment, polymers and cross-linked gels bearing electron-withdrawing substituents can be fully degraded under basic conditions. These control-

lable and degradable features in polymerization pave the way for sustainable polysulfates with desired mechanical properties.

## METHODS

**Procedure for the Synthesis of the Model Polymer (0.5 mmol scale).** To a flame-dried 4 mL vial equipped with a magnetic stirrer, AB-type monomer (M, 25–300 equiv) – MeEst (154  $\mu$ L,  $d$  = 1.184) and iminosulfur oxydifluoride initiator (I, 1 equiv, 0.37–4.44 mg) from stock solution were premixed with 500  $\mu$ L of butyronitrile (1 M to monomer, dried with activated 4  $\text{\AA}$  molecular sieves). The vial was sealed with septum cap and placed at the desired temperature (90  $^{\circ}\text{C}$ ) for 5 min. Then, a catalyst from another batch of a stock solution (0.5 M of DBU in butyronitrile, 1 equiv) was quickly injected into a reaction mixture as one shot to initiate polymerization. For the high M/I of 200 and 300, a stock solution—premixed 1:1 mixture of initiator and DBU—was injected as one-shot to a prewarmed reaction mixture to initiate polymerization. The polymerization occurred at the desired temperature with stirring until the full consumption of monomer, and the mixture was precipitated into MeOH twice. The resulting polymer was dried under a vacuum affording a white solid (for M/I = 50:  $M_n$  = 11.9 k, and  $D$  = 1.28, 95% yield). The precipitated polymer was characterized by SEC, MALDI-TOF, and  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{19}\text{F}$  NMR. Full experimental details and characterization of compounds are given in the [Supporting Information](#).

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acscentsci.1c01015>.

Experimental details, synthesis, optimization tables, characterization data (TGA, DSC, SEC traces etc.), and spectra of the compounds ([PDF](#))

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### Author Contributions

K.B.S. and P.W. supervised the work. H.K. designed the experiments and performed the synthesis and characterization of the polymers. P.W. provided helpful suggestions on the project. J.Z. and J.B. collected and analyzed physical properties of gels. L.M.K., E.A.D., and Y.L. collected TGA and DSC data of all polymers and measured absolute molecular weight of polymers. H.K. wrote the manuscript, and all authors edited the manuscript.

### Notes

The authors declare no competing financial interest.

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## REFERENCES

- (1) Staudinger, H. Über polymerisation. *Ber. Dtsch. Chem. Ges.* **1920**, *53*, 1073–1085.
- (2) Mülhaupt, R. Hermann Staudinger and the origin of macromolecular chemistry. *Angew. Chem., Int. Ed.* **2004**, *43*, 1054–1063.
- (3) Carothers, W. H. Studies on polymerization and ring formation. I. An introduction to the general theory of condensation polymers. *J. Am. Chem. Soc.* **1929**, *51*, 2548–2559.
- (4) Carothers, W. H. Polymers and polyfunctionality. *Trans. Faraday Soc.* **1936**, *32*, 39–49.
- (5) Carothers, W. H. Polymerization. *Chem. Rev.* **1931**, *8*, 353–426.
- (6) Smith, J. K.; Hounshell, D. A. Wallace H. Carothers and fundamental research at Du Pont. *Science* **1985**, *239*, 436–442.
- (7) Yokozawa, T.; Asai, T.; Sugi, R.; Ishigooka, S.; Hiraoka, S. Chain-growth polycondensation for nonbiological polyamides of defined architecture. *J. Am. Chem. Soc.* **2000**, *122*, 8313–8314.
- (8) Ohishi, T.; Sugi, R.; Yokoyama, A.; Yokozawa, T. Synthesis via Chain-Growth Condensation Polymerization and Gelating Properties of a Variety of Block Copolymers of Meta-and Para-Substituted Aromatic Polyamides. *Macromolecules* **2008**, *41*, 9683–9691.
- (9) Ohta, Y.; Kamijyo, Y.; Fujii, S.; Yokoyama, A.; Yokozawa, T. Synthesis and Properties of a Variety of Well-Defined Hyperbranched N-Alkyl and N-H Polyamides by Chain-Growth Condensation Polymerization of AB<sub>2</sub> Monomers. *Macromolecules* **2011**, *44*, 5112–5122.
- (10) Yokozawa, T.; Suzuki, Y.; Hiraoka, S. Aromatic polyethers with low polydispersities from chain-growth polycondensation. *J. Am. Chem. Soc.* **2001**, *123*, 9902–9903.
- (11) Suzuki, Y.; Hiraoka, S.; Yokoyama, A.; Yokozawa, T. Chain-growth polycondensation for aromatic polyethers with low poly-

dispersities: Living polymerization nature in polycondensation. *Macromolecules* **2003**, *36*, 4756–4765.

(12) Ajioka, N.; Suzuki, Y.; Yokoyama, A.; Yokozawa, T. Synthesis of well-defined polystyrene-*b*-aromatic polyether using an orthogonal initiator for atom transfer radical polymerization and chain-growth condensation polymerization. *Macromolecules* **2007**, *40*, 5294–5300.

(13) Yokoyama, A.; Iwashita, K.-i.; Hirabayashi, K.; Aiyama, K.; Yokozawa, T. Investigation of aromatic polyester synthesis by the chain-growth polycondensation method. *Macromolecules* **2003**, *36*, 4328–4336.

(14) Yokozawa, T.; Taniguchi, T.; Suzuki, Y.; Yokoyama, A. Chain-growth polycondensation of monomer consisting of two aromatic rings: Synthesis of well-defined poly(ether sulfone) from 4-fluoro-4'-hydroxydiphenyl sulfone. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 3460–3464.

(15) Yokoyama, A.; Miyakoshi, R.; Yokozawa, T. Chain-growth polymerization for poly(3-hexylthiophene) with a defined molecular weight and a low polydispersity. *Macromolecules* **2004**, *37*, 1169–1171.

(16) Yokozawa, T.; Yokoyama, A. Chain-growth polycondensation: living polymerization nature in polycondensation and approach to condensation polymer architecture. *Polym. J.* **2004**, *36*, 65–83.

(17) Yokoyama, A.; Yokozawa, T. Converting step-growth to chain-growth condensation polymerization. *Macromolecules* **2007**, *40*, 4093–4101.

(18) Yokozawa, T.; Ohta, Y. Transformation of step-growth polymerization into living chain-growth polymerization. *Chem. Rev.* **2016**, *116*, 1950–1968.

(19) Yokozawa, T.; Ohta, Y. Chapter 1: Controlled Synthesis of Conjugated Polymers in Catalyst-transfer Condensation Polymerization: Monomers and Catalysts. *Semiconducting Polymers: Controlled Synthesis and Microstructure* **2016**, 1–37.

(20) Fu, L.; Xu, M.; Yu, J.; Gutekunst, W. R. Halide-Rebound Polymerization of Twisted Amides. *J. Am. Chem. Soc.* **2019**, *141*, 2906–2910.

(21) Kosaka, K.; Uchida, T.; Mikami, K.; Ohta, Y.; Yokozawa, T. AmPhos Pd-Catalyzed Suzuki–Miyaura Catalyst-Transfer Condensation Polymerization: Narrower Dispersity by Mixing the Catalyst and Base Prior to Polymerization. *Macromolecules* **2018**, *51*, 364–369.

(22) Yokozawa, T.; Kohno, H.; Ohta, Y.; Yokoyama, A. Catalyst-Transfer Suzuki–Miyaura Coupling Polymerization for Precision Synthesis of Poly(*p*-phenylene). *Macromolecules* **2010**, *43*, 7095–7100.

(23) Yano, Y.; Mitoma, N.; Matsushima, K.; Wang, F.; Matsui, K.; Takakura, A.; Miyauchi, Y.; Ito, H.; Itami, K. Living annulative pi-extension polymerization for graphene nanoribbon synthesis. *Nature* **2019**, *571*, 387–392.

(24) Kang, J.; Miyajima, D.; Mori, T.; Inoue, Y.; Itoh, Y.; Aida, T. A rational strategy for the realization of chain-growth supramolecular polymerization. *Science* **2015**, *347*, 646–651.

(25) Qin, A.; Lam, J. W.; Tang, B. Z. Click polymerization. *Chem. Soc. Rev.* **2010**, *39*, 2522–2544.

(26) Wu, P.; Feldman, A. K.; Nugent, A. K.; Hawker, C. J.; Scheel, A.; Voit, B.; Pyun, J.; Fréchet, J. M.; Sharpless, K. B.; Fokin, V. V. Efficiency and fidelity in a click-chemistry route to triazole dendrimers by the copper (I)-catalyzed ligation of azides and alkynes. *Angew. Chem., Int. Ed.* **2004**, *43*, 3928–3932.

(27) Díaz, D. D.; Punna, S.; Holzer, P.; McPherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. Click chemistry in materials synthesis. 1. Adhesive polymers from copper-catalyzed azide-alkyne cycloaddition. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4392–4403.

(28) Xi, W.; Scott, T. F.; Kloxin, C. J.; Bowman, C. N. Click chemistry in materials science. *Adv. Funct. Mater.* **2014**, *24*, 2572–2590.

(29) Lee, I.-H.; Kim, H.; Choi, T.-L. Cu-catalyzed multicomponent polymerization to synthesize a library of poly(*N*-sulfonylamidines). *J. Am. Chem. Soc.* **2013**, *135*, 3760–3763.

(30) Kim, H.; Choi, T.-L. Preparation of a library of poly(*N*-sulfonylimidates) by Cu-catalyzed multicomponent polymerization. *ACS Macro Lett.* **2014**, *3*, 791–794.

(31) Liu, X.; Han, T.; Lam, J. W.; Tang, B. Z. Functional Heterochain Polymers Constructed by Alkyne Multicomponent Polymerizations. *Macromol. Rapid Commun.* **2021**, *42*, 2000386.

(32) Kim, H.; Bang, K.-T.; Choi, I.; Lee, J.-K.; Choi, T.-L. Diversity-oriented polymerization: one-shot synthesis of library of graft and dendronized polymers by Cu-catalyzed multicomponent polymerization. *J. Am. Chem. Soc.* **2016**, *138*, 8612–8622.

(33) Shi, Y.; Graff, R. W.; Cao, X.; Wang, X.; Gao, H. Chain-growth click polymerization of AB<sub>2</sub> monomers for the formation of hyperbranched polymers with low polydispersity in a one-pot process. *Angew. Chem., Int. Ed.* **2015**, *54*, 7631–7635.

(34) Gan, W.; Cao, X.; Shi, Y.; Gao, H. Chain-growth polymerization of azide–alkyne difunctional monomer: Synthesis of star polymer with linear polytriazole arms from a core. *J. Polym. Sci.* **2020**, *58*, 84–90.

(35) Dong, J.; Sharpless, K. B.; Kwisnek, L.; Oakdale, J. S.; Fokin, V. V. SuFEx-Based Synthesis of Polysulfates. *Angew. Chem., Int. Ed.* **2014**, *53*, 9466–9470.

(36) Barrow, A.; Smedley, C.; Zheng, Q.; Li, S.; Dong, J.; Moses, J. The growing applications of SuFEx click chemistry. *Chem. Soc. Rev.* **2019**, *48*, 4731–4758.

(37) Gao, B.; Zhang, L.; Zheng, Q.; Zhou, F.; Klivansky, L. M.; Lu, J.; Liu, Y.; Dong, J.; Wu, P.; Sharpless, K. B. Bifluoride-catalysed sulfur (VI) fluoride exchange reaction for the synthesis of polysulfates and polysulfonates. *Nat. Chem.* **2017**, *9*, 1083–1088.

(38) Wang, H.; Zhou, F.; Ren, G.; Zheng, Q.; Chen, H.; Gao, B.; Klivansky, L.; Liu, Y.; Wu, B.; Xu, Q.; Lu, J.; Sharpless, K. B.; Wu, P. SuFEx-Based Polysulfonate Formation from Ethenesulfonyl Fluoride–Amine Adducts. *Angew. Chem., Int. Ed.* **2017**, *56*, 11203–11208.

(39) Li, S.; Li, G.; Gao, B.; Pujari, S. P.; Chen, X.; Kim, H.; Zhou, F.; Klivansky, L. M.; Liu, Y.; Driss, H.; et al. SuFExable polymers with helical structures derived from thionyl tetrafluoride. *Nat. Chem.* **2021**, *13*, 858–867.

(40) Xu, L.; Wu, P.; Dong, J. CHAPTER 1: New Polymers From SuFEx Click Chemistry: Syntheses and Perspectives. *Synthetic Polymer Chemistry: Innovations and Outlook* **2019**, 1–31.

(41) Li, S.; Wu, P.; Moses, J. E.; Sharpless, K. B. Multidimensional SuFEx click chemistry: sequential sulfur (VI) fluoride exchange connections of diverse modules launched from an SOF<sub>4</sub> hub. *Angew. Chem., Int. Ed.* **2017**, *56*, 2903–2908.

(42) Sugi, R.; Yokoyama, A.; Furuyama, T.; Uchiyama, M.; Yokozawa, T. Inductive Effect-Assisted Chain-Growth Polycondensation. Synthetic Development from para-to meta-Substituted Aromatic Polyamides with Low Polydispersities. *J. Am. Chem. Soc.* **2005**, *127*, 10172–10173.

(43) Ohishi, T.; Sugi, R.; Yokoyama, A.; Yokozawa, T. A variety of poly(*m*-benzamide)s with low polydispersities from inductive effect-assisted chain-growth polycondensation. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 4990–5003.

(44) Esser-Kahn, A. P.; Odom, S. A.; Sottos, N. R.; White, S. R.; Moore, J. S. Triggered release from polymer capsules. *Macromolecules* **2011**, *44*, 5539–5553.

(45) Li, J.; Mooney, D. J. Designing hydrogels for controlled drug delivery. *Nat. Rev. Mater.* **2016**, *1*, 1–17.

(46) Gillies, E. R.; Fréchet, J. M. Dendrimers and dendritic polymers in drug delivery. *Drug Discovery Today* **2005**, *10*, 35–43.

(47) Fu, K. K.; Wang, Z.; Dai, J.; Carter, M.; Hu, L. Transient electronics: materials and devices. *Chem. Mater.* **2016**, *28*, 3527–3539.

(48) Cao, Z.; Zhou, F.; Gu, P.-Y.; Chen, D.; He, J.; Cappiello, J. R.; Wu, P.; Xu, Q.; Lu, J. Preparation of aryl polysulfonates via a highly efficient SuFEx click reaction, their controllable degradation and functionalized behavior. *Polym. Chem.* **2020**, *11*, 3120–3124.

(49) Kulow, R. W.; Wu, J. W.; Kim, C.; Michaudel, Q. Synthesis of unsymmetrical sulfamides and polysulfamides via SuFEx click chemistry. *Chem. Sci.* **2020**, *11*, 7807–7812.

(50) Liu, C.; Yang, C.; Hwang, S.; Ferraro, S. L.; Flynn, J. P.; Niu, J. A General Approach to *O*-Sulfation by a Sulfur (VI) Fluoride Exchange Reaction. *Angew. Chem., Int. Ed.* **2020**, *59*, 18435–18441.

(51) Feist, J. D.; Xia, Y. Enol Ethers Are Effective Monomers for Ring-Opening Metathesis Polymerization: Synthesis of Degradable and Depolymerizable Poly(2,3-dihydrofuran). *J. Am. Chem. Soc.* **2020**, *142*, 1186–1189.

(52) Xu, Y.; Sen, S.; Wu, Q.; Zhong, X.; Ewoldt, R. H.; Zimmerman, S. C. Base-triggered self-amplifying degradable polyurethanes with the ability to translate local stimulation to continuous long-range degradation. *Chem. Sci.* **2020**, *11*, 3326–3331.

(53) Shieh, P.; Nguyen, H. V.; Johnson, J. A. Tailored silyl ether monomers enable backbone-degradable polynorbornene-based linear, bottlebrush and star copolymers through ROMP. *Nat. Chem.* **2019**, *11*, 1124–1132.

(54) Shieh, P.; Zhang, W.; Husted, K. E. L.; Kristufek, S. L.; Xiong, B.; Lundberg, D. J.; Lem, J.; Veysset, D.; Sun, Y.; Nelson, K. A.; et al. Cleavable comonomers enable degradable, recyclable thermoset plastics. *Nature* **2020**, *583*, 542–547.

(55) Amamoto, Y.; Kamada, J.; Otsuka, H.; Takahara, A.; Matyjaszewski, K. Repeatable photoinduced self-healing of covalently cross-linked polymers through reshuffling of trithiocarbonate units. *Angew. Chem., Int. Ed.* **2011**, *50*, 1660–1663.

(56) Lu, Y.-X.; Guan, Z. Olefin metathesis for effective polymer healing via dynamic exchange of strong carbon–carbon double bonds. *J. Am. Chem. Soc.* **2012**, *134*, 14226–14231.

(57) Garcia, J. M.; Jones, G. O.; Virwani, K.; McCloskey, B. D.; Boddy, D. J.; ter Huurne, G. M.; Horn, H. W.; Coady, D. J.; Bintaleb, A. M.; Alabdulrahman, A. M. S.; Alsewailem, F.; Almegren, H. A. A.; Hedrick, J. L. Recyclable, strong thermosets and organogels via paraformaldehyde condensation with diamines. *Science* **2014**, *344*, 732–735.