Pure Appl. Chem., Vol. 85, No. 3, pp. 557–571, 2013.
http://dx.doi.org/10.1351/PAC-CON-12-04-09

Synthesis of multifunctional polymers by combination of controlled radical polymerization (CRP) and effective polymer analogous reactions*

Maria Riedel[1,2] and Brigitte Voit[1,2,‡]

[1]Leibniz-Institut für Polymerforschung Dresden e.V., Hohe Strasse 6, D-01069 Dresden, Germany; [2]Organic Chemistry of Polymers, Technische Universität Dresden, D-01062 Dresden, Germany

Abstract: The combination of controlled radical polymerization (CRP) reactions and click chemistry offers high potential for the preparation of multifunctional polymers and significantly broadens the application scope of functional soft matter materials. In order to demonstrate the strategies as well as the potential of this methodology combination, examples for end-group and side-chain modification of polymers produced by CRP methods and the use of the resulting materials in functional polymer films are given.

Keywords: click chemistry; controlled radical polymerization (CRP); multifunctionality; polymer chemistry; thin films.

INTRODUCTION

In the last decade, the combination of controlled radical polymerization (CRP) techniques (nitroxide-mediated radical polymerization (NMRP) [1], reversible addition-fragmentation chain transfer (RAFT) [2,3], atom-transfer radical polymerization (ATRP) [4]) and highly effective and selective organic reactions termed as the "click chemistry" [5] have been demonstrated to be a versatile tool for the specific construction of novel functional macromolecules [6]. The large number of reviews already published in the meantime and the impressive number of research groups active in this field underlines the importance of this methodology in polymer science [5–20].

In 2001, Sharpless et al. [5] introduced the term "click chemistry" with its famous representative, the cycloaddition of azides with alkynes under Cu catalysis [21]. He defined a "click reaction" with a set of criteria: "The reaction must be modular, wide in scope, give very high yields, generate only inoffensive byproducts that can be removed by nonchromatographic methods, and be stereospecific (but not necessarily enantioselective)" with further specifications for easy-to-realize reaction conditions and easy product isolation.

The most well-known reactions satisfying the philosophy of click chemistry are, besides the most popular 1,3-cycloaddition between azides and alkynes, thiol-ene, oxime, Diels–Alder, and pyridyl disulfide reactions as well as the Michael addition and activated ester coupling. Although Sharpless has seen the application of click chemistry mainly in the pharmaceutical area, very fast, click reactions were

Pure Appl. Chem.* **85, 493–587 (2013). A collection of invited papers based on presentations at the 14th International Conference on Polymers and Organic Chemistry (POC 2012), Doha, Qatar, 6–9 January 2012.
‡Corresponding author

established also in the field of polymer chemistry [22,23], since click reactions suddenly offer a feasible pathway especially where other polymer synthesis techniques come to their limits. The end-group functionalization of polymers by click chemistry enables a wide diversity of functional soft materials comprising also the linking of incompatible polymer chains and preparation of biohybrids [18,24,25]. It is particularly important that these reactions are highly effective, because of the small quantity of functional end-groups in polymer chains. Furthermore, the click reaction is used in numerous examples for the introduction of functional side-chains and functionalities in linear and dendritic polymers [26–28], whereby such reactions again need a high effectiveness and selectivity in order to lead to homogeneous materials, especially since functionalities attached onto polymer chains are usually characterized by lower reactivity. Another field of research is the direct construction of so-far-inaccessible linear and dendritic polymers with the help of click reactions [29,30].

Due to the rather easy accessibility of novel functional polymer materials by click reactions, their potential scope of applications has significantly broadened in the last years. Through the preparation of functional thin polymer films [31–33], biohybrid or self-assembly structures [34] from end-group or side-chain functionalized polymers and functional block copolymers, applications, e.g., as adhesives or additives, but especially also in optoelectronics, biomedicines, drug delivery, biochips, and micro- and nanoelectronics, become accessible [35].

The fast development of click chemistry leads of course also to the search for new reactions expanding the scope. Unfortunately, the term "click" is used in the meantime rather carelessly and is applied also for reactions, which often do not lead to high conversions or require tedious purification procedures. Therefore, Barner-Kowollik and colleagues [7] have taken care of classifying "click chemistry" especially for the field of polymer synthesis. In their opinion, "click" is often taken just as synonym for "efficient" or "successful", but not all efficient reactions can be classified to be click reactions. With regard to polymer chemistry, they further refined the original criteria in the following way: "Single reaction trajectory, chemoselective, wide in scope, modular, stable compounds, high yields, fast timescale, large-scale purification, equimolarity". The first four requirements are taken without alteration from Sharpless' original definition, whereas the remaining criteria are adapted to requirements from synthetic polymer chemistry.

In this article we will demonstrate the possibilities given by the combination of CRP reactions and click chemistry for the preparation of multifunctional polymers by focusing on own work in the field. Early on, the synthesis of diverse dendritic structures by Cu(I)-catalyzed reaction of azides and alkynes was demonstrated by us and others [23,30,36]. AB_2 monomers based on terminal alkynes and alkyl halide functionalities were used to build sequentially the dendrons by a convergent approach. Later on, the modification and construction of copolymers as well as block copolymers by making use of various CRP techniques and highly efficient organic reactions dominated our activities, especially for being able to design new materials for use as multifunctional and nanostructured thin films. In the following section, we will thus focus on examples from end-group and side-chain modification of polymers produced by CRP methods and the use of the resulting materials in functional polymer films.

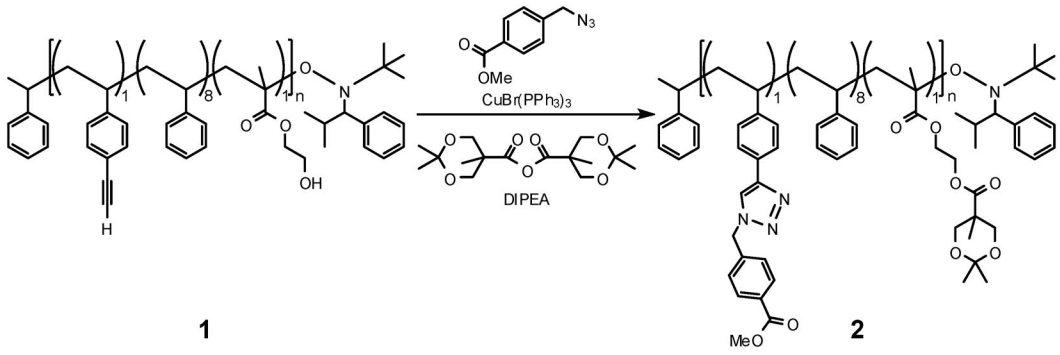
SIDE-CHAIN MODIFICATION OF POLYMERS VIA CLICK REACTIONS

The click reaction enables the postfunctionalization of polymers through introduction of functional groups. Here, it is important that the reaction has near quantitative yield, high selectivity, and the potential for regiospecificity.

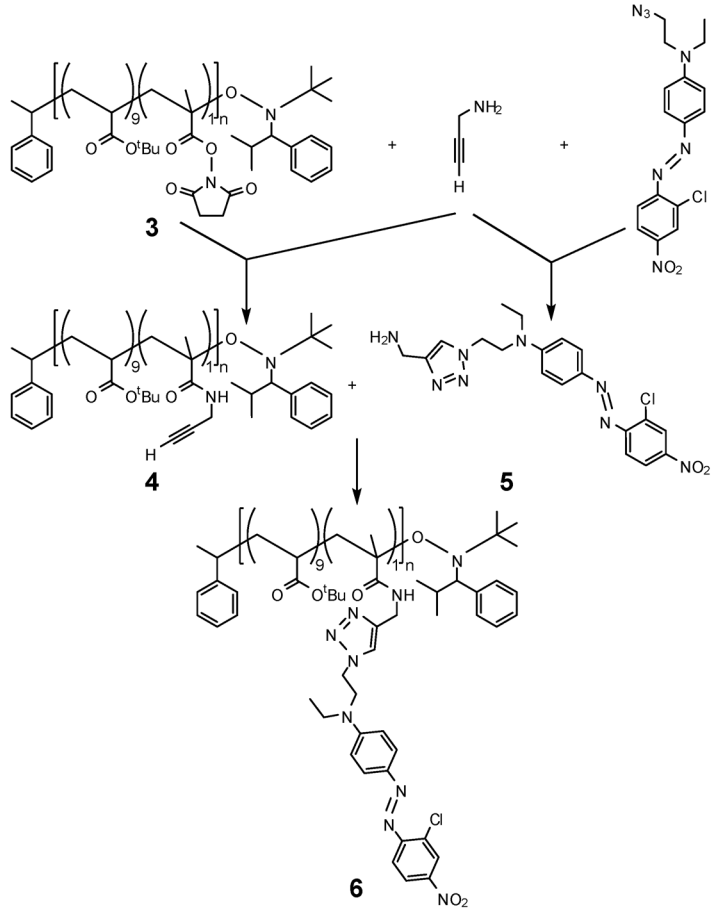
We were introduced in the field when in 2005 Hawker and co-workers [29] explored cascade and simultaneous strategies for the orthogonal functionalization of polymers. At first they synthesized copolymers via NMRP with different functional monomers like ethynylvinylbenzene, hydroxyethyl methacrylate, or *N*-acryloyloxy succinimide. For the postmodification of the polymers, on the one hand, the Cu(I)-catalyzed 1,3-dipolar cycloaddition of azides and alkynes and an esterification to introduce two different molecules in a polymer in a one-pot reaction was used. On the other hand, a cascade strat-

egy was developed to functionalize the polymers. In this approach, a functional group **X** on the backbone reacts with a linker molecule **Y** and a terminal group **Z** to give the cascade functionality **X-Y-Z**.

In Schemes 1 and 2, examples of such simultaneous and cascade reactions are shown.



Scheme 1 Simultaneous polymer analogous reaction [29].



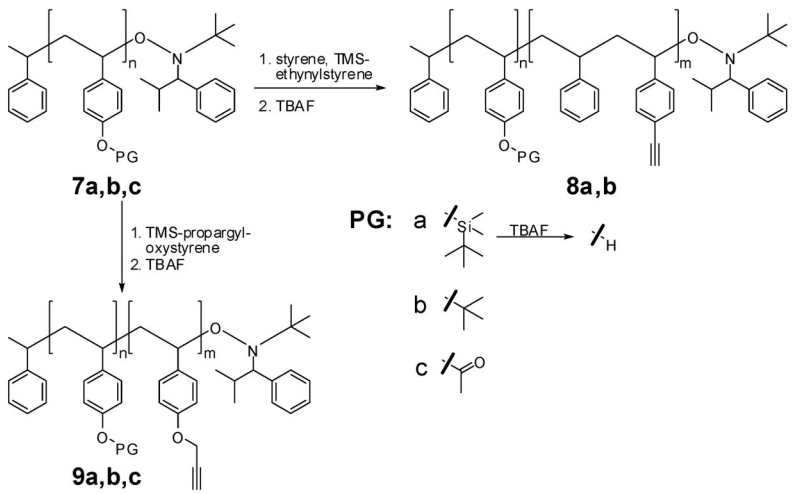
Scheme 2 Polymer analogous cascade reaction [29].

The simultaneous reaction of **1** shows the conversion of the acetylene and hydroxyl functionality into a methyl-benzoate-substituted triazole group and an acetonide-protected 2,2-bis(hydroxylmethyl)-propionic ester, respectively. In NMR and IR measurements, a greater than 95 % functionalization of both functionalities was realized. In addition, no unwanted side-reactions had been detected. Another example based on click reaction on a propargyl-substituted acrylamide combined with an esterification on a hydroxyl group with 1-azido-1-deoxy-β-D-glucopyranoside tetraacetate and succinimidyloxy 4-methoxybenzoate shows again the completely quantitative and simultaneous functionalization of both groups of the polymer. This concept allows, because of its modular nature, the construction of a wide range of different backbones and functional groups.

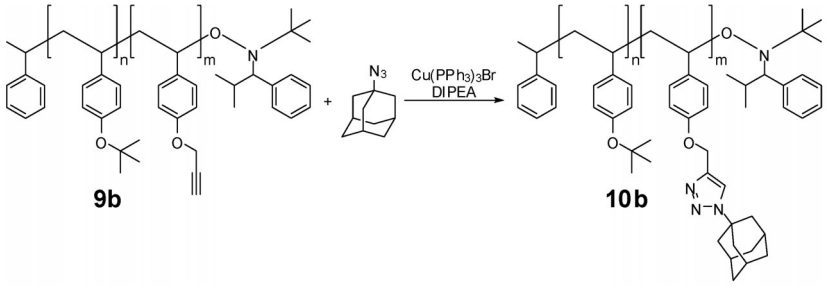
The cascade reaction was carried out with the copolymer **3** and propargylamine as well as 2-[4-(2'-chloro-4'-nitrophenylazo)-*N*-ethylphenylamino]ethyl azide. The Cu(I) acts as catalyst for the click reaction between propargylamine and the azide component to give **5** as well as between the intermediate coupling products **4** and **5**, while DIPEA catalyzes the amidation of **3** with propargylamine to give **4** or the reaction of **4** with **5** to give **6**. Gel permeation chromatography/high-performance liquid chromatography (GPC/HPLC) and NMR measurements showed a complete conversion for all reactions. Variations of the structure of functional monomer, linker, and terminal group show also the effectiveness of this reaction and demonstrate so the modularity of this strategy. Hawker et al. [6] summarized the recent developments in this field and demonstrated the high potential of efficient orthogonal reactions for the preparation of functional soft materials.

The recent developments in nanotechnology offer also a high potential for phase-separated block copolymers, e.g., as templates for nanostructured materials. In combination with click chemistry, these block copolymers represent a promising scaffold in macromolecular engineering for novel functional nanostructured polymer materials and for patterning on the nanoscale with various functionality.

Thus, we [37] developed diblock copolymers, making them candidates for block copolymer lithography and polymer analogous modification reactions. Different alkyne-containing diblock copolymers based on 4-hydroxystyrene were synthesized by NMRP, which can phase-separate. The first block bears the labile protected 4-hydroxystyrene, whereas the second block consists of alkyne functionalities (Scheme 3). These alkyne functionalities can be converted in a click reaction which allows creation of a thin nanostructured film where the nanoscopic domains might be exclusively addressed by orthogonal reaction techniques. In order to demonstrate the principle, a click reaction of such a block copolymer as seen in Scheme 4 was carried out with bulky 1-adamantyl azide. NMR and GPC measurements proved a full conversion and the absence of side-reactions.

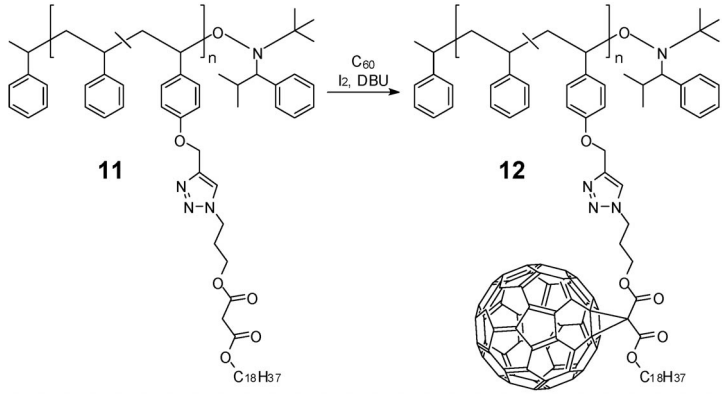


Scheme 3 Examples of diblock copolymers for click modification [37].



Scheme 4 Polymer analogous click reaction on block copolymers with bulky adamantyl azide [37].

Based on alkyne-containing polymers, recently [38] acceptor polymers were developed for application in donor–acceptor block copolymers. The most popular acceptor moiety is fullerene, because of its outstanding electrochemical properties. So random copolymers of styrene and propargyloxystyrene were synthesized, which were modified by azide-containing functional fullerene derivatives. Requirements for these materials were the inclusion of a linker group as well as the need for a potentially variable solubilizing group. In a first approach, it was planned to integrate the fullerene in an asymmetric malonate ester with a "clickable" azide functionality, however, synthetic realization of such a compound in a reliable way proved impossible. Therefore, in a second approach the precursor polymer was modified first by a click reaction with a malonate residue to obtain **11** (Scheme 5). For the click reaction the poly(styrene-r-4-propargyloxystyrene) reacted with 3-azidopropyloctadecyl malonate using Cu(I) and *N*,*N*-diisopropylethylamine (DIPEA) as catalyst system. The efficiently modified polymer **11** was then transformed in a Bingel reaction with pure fullerene C_{60} (Scheme 5).

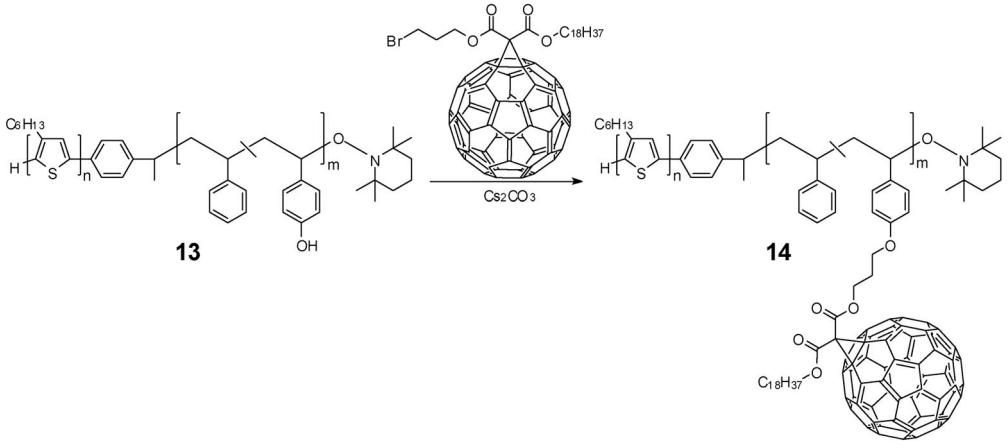


Scheme 5 Bingel reaction with fullerene on a "click"-modified polymer [38].

In further work, another method to bind fullerene C_{60} onto polymers was investigated [39]. Copolymers based on styrene and comonomers with hydroxyl functionality were prepared by NMRP and then transformed in a Williamson ether synthesis using a bromine-functionalized malonate ester fullerene derivative and Cs carbonate. Cs salts are very reactive because of their exceptional high nucleophilicity ("cesium effect"). They are used in the organic chemistry as efficient reactions under mild conditions for the preparation of ethers and esters [40–43]. In 2010 [44], this reaction was employed firstly for efficient polymer analogous modifications.

The Cs-mediated polymer analogous reaction was further adapted for the preparation of donor–acceptor block copolymer materials. First, a 2,2,6,6-tetra-methyl-piperidine-*N*-oxyl (TEMPO)

end-functionalized poly(3-hexylthiophene) (P3HT) macroinitiator was prepared via Kumada-catalyst transfer polycondensation [45]. The block copolymer **13** was obtained via the P3HT macroinitiator by NMRP of styrene and protected hydroxystyrene with subsequent deprotection. In Scheme 6, the etherification of the hydroxyl functionality of the block copolymer **13** with the bromine-functionalized fullerene derivate is shown [39].



Scheme 6 Donor–acceptor block copolymers through Cs-mediated esterification [39].

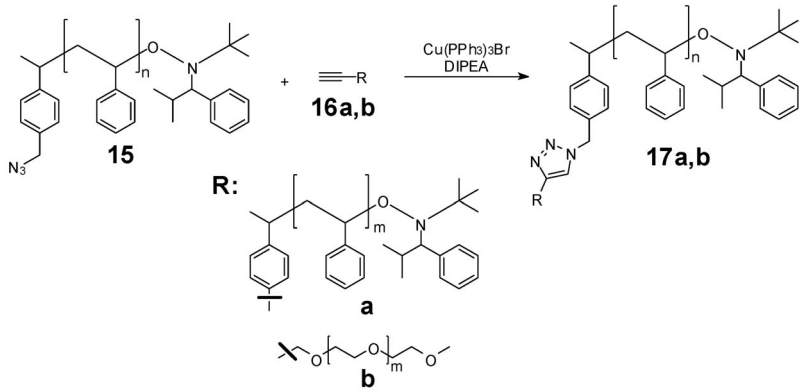
END-GROUP MODIFICATION OF POLYMERS VIA CLICK REACTIONS

Besides the modification of polymers at the side-groups via click reactions, another important topic is the introduction of functional end-groups or the click reaction between different polymer chains through end-groups. This concept enables the linking of two different polymers, which are not able to polymerize in the traditional sense (e.g., block copolymerization by subsequent monomer addition). Hybrid polymers of biological and synthetic source are also imaginable [18,46–49].

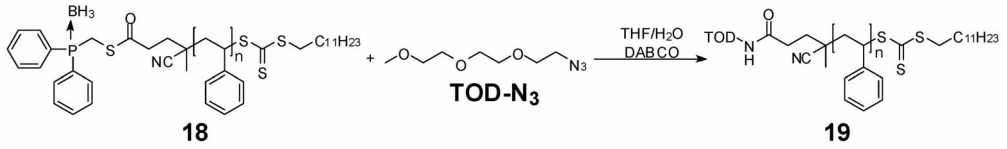
In order to demonstrate this concept early on [50], we investigated the end-group modification of synthesized polymers to click them in a polymer analogous reaction. At first, polymers were synthesized via NMRP bearing an α-terminated alkyne as well as an azide group. Alkyne end-functionalized polystyrene (**16a**) was synthesized using a protected alkyne-functionalized 2,2,5-tri-methyl-4-phenyl-3-azahexane-3-nitroxide (TIPNO) initiator with subsequent removal of the trimethylsilyl (TMS) group by tetrabutylammonium fluoride (TBAF). For the azide end-functionalized polymer (**15**), styrene was polymerized with a vinylbenzyl chloride-derived TIPNO initiator and subsequently reacted with sodium azide [51]. The alkyne end-functionalized polystyrene **16a** was modified with model azides to demonstrate the ability of click chemistry to combine predefined blocks of different chemistry. Because of the full conversion, the synthesis of hybrid block copolymers can be efficiently achieved by coupling predefined blocks with suitable end-functionality via click chemistry.

In Scheme 7, the successful click reaction between an azide end-functionalized polystyrene (**15**) and an alkyne end-functionalized polystyrene (**16a**) as well as polyethylene glycol (**16b**) is shown.

Disadvantages of the traditional click reaction of azides with alkynes are the need of Cu and the formation of the triazole ring which might cause problems especially with regard to the use for the preparation of biohybrid material or for use in biomedicine. An alternative could be the Staudinger ligation, which is a special case of an aza-Wittig reaction [52]. We [53] demonstrated the unique combination of RAFT polymerization and Staudinger ligation. New RAFT agents were synthesized, which contain a phosphine end-group for the polymer analogous Staudinger ligation. The phosphine group was inserted via esterification in carboxyl-functionalized chain transfer agents (CTAs). The main diffi-



Scheme 7 Click reaction between two polymers [50].



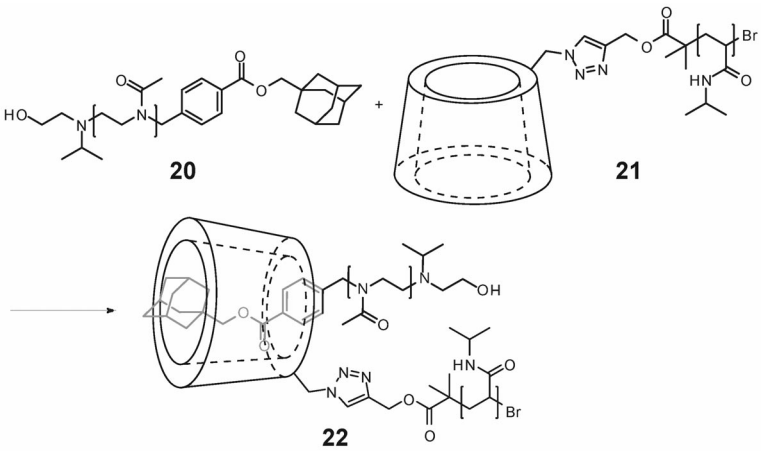
Scheme 8 Polymer-coupling using the Staudinger ligation [53].

culties of the CTAs were on the one hand, the oxidation sensitivity of the phosphine group during the polymerization process and on the other hand the sterical hindrance in the α-position of the ester group. To inhibit the oxidation of the phosphine group, the group is protected by a borane group. Furthermore, a CTA was used with no substituent in the α-position of the ester group. Such a CTA was then used for the polymerization of styrene. This polystyrene (**18**) was reacted with the model compound 3,6,9-trioxydecyl azide (**TOD-N3**) in a Staudinger ligation (Scheme 8).

NMR measurements showed that no phosphine groups were left in the modified polymer. The degree of conversion was determined to be 82 %. Taking into account that 12 % of the phosphine groups of polymer **18** were oxidized during the polymerization and that 6 % of the phosphine groups originally present in the unprotected state might have been oxidized while storing, one can assume that the polymer analogous reaction had been accomplished in a quantitative manner. However, one has to state that the synthetic effort for the synthesis of suitable RAFT agents limits the use of the Staudinger ligation in the polymer synthesis. Alternatively, the also Cu-free thiol-ene reaction has demonstrated to be of high potential in various preparations of biohybrids and functional block copolymers for potential biomedical application [49].

Another unconventional method to build diblock copolymers is the noncovalent linkage via complexation of β-cyclodextrin (β-CD) and adamantane end-functionalized polymers. CDs are of particular interest because of the high binding forces in host–guest inclusions with adamantyl groups. This concept was demonstrated [54] on two water-soluble polymers [poly(2-methyl-2-oxazoline) (PMeOxa) and poly(*N*-isopropyl-acrylamide (PNIPAAm)], which are end-group-modified with adamantane and β-CD, respectively. The adamantane-functionalized PMeOxa (**20**) was synthesized by a cationic polymerization. The initiator was obtained via esterification of 4-bromomethylbenzoyl bromide with 1-adamantanemethanol. For the β-CD-functionalized PNIPAAm (**21**), an azide-functionalized β-CD was synthesized according to ref. [28]. This monoazide-functionalized β-CD was clicked with 2-promoisobutyryl propargylester to yield the ATRP initiator for the controlled polymerization of *N*-isopropylacrylamide (NIPAAm). The complexation of adamantyl groups of **20** was at first studied by β-CD. The interactions were verified by ^{1}H NMR spectroscopy. The analysis of a ROESY spectrum

showed that the whole adamantyl end-group together with the benzoyl spacer is included into the slightly narrower side of the β-CD ring. The complexation of the two polymers **20** and **21** (Scheme 9) was followed by titration of **20** with **21** and **21** with **20** by NMR. The changes in signal position and shape of the benzoyl protons, the β-CD protons, and the adamantane protons indicated an increasing content of complexed adamantane moieties. At equimolar ratio of guest and host end-group in both titrations, the same spectra were obtained. Because of similar changes observed for the benzoyl proton signals in the complexation of **20** with free β-CD and in the complexation of **20** with **21**, it is suggested that in the polymer–polymer complexation, the adamantyl end-group is included in the β-CD cavity from the narrower side. A direct prove of this insertion mode cannot be presented, because a ROESY spectrum of the polymer complex gives no evaluable correlation peaks.



Scheme 9 Complexation of adamantyl end-functionalized polymer (**20**) with a β-CD end-functionalized polymer (**21**) [54].

THIN FUNCTIONAL AND NANOSTRUCTURED FILMS

The previously presented examples in this article have shown the effectiveness of the combination of the synthesis of polymers by CRP techniques with the subsequent modification of these polymers by efficient polymer analogous reactions. The preparation of phase-separating block copolymers with selective functionalization in one block is especially very promising. In the following section, we would like to give examples how polymers, prepared by the above-outlined approaches, can be applied in thin film technology for functional patterning with high fidelity and structuring on the nanoscale. A broad variety of examples can be found today in the literature on this topic [32,55,56], and thus again, we will focus on our own work.

As mentioned before, the combination of CRP and click chemistry can provide a huge number of new polymer materials, which are not accessible with traditional methods. Dendronized polymers are such an example, because their traditional synthesis is time-consuming and does not always lead to the desired control over the macromolecular architecture. Dendronized polymers are of special interest regarding the formation of rod-coil-type diblock copolymers when the dendritic side-chains are introduced only in one block. Through polymer analogous click reactions, highly defined dendronized diblock copolymers have been synthesized [57] and their phase separation behavior in thin films was investigated. Here, a dendritic azide (Fréchet benzyl type) [58] of three different generations instead of the adamantyl azide was "clicked" onto polymer **9b** (Scheme 4). DSC measurements identified only a single glass-transition temperature (T_g) in the strong asymmetric precursor block copolymer **9b**. However, the decorated polymer backbone with dendrons of first (**9b-G1**), second (**9b-G2**), and third

(**9b-G3**) generation, respectively, results in a considerable phase separation of the diblock copolymer, and two distinct T_gs were identified. In Fig. 1, the atomic force microscopy (AFM) phase images of the resulting thin films of the precursor and the three dendronized diblock copolymers, respectively, are shown.

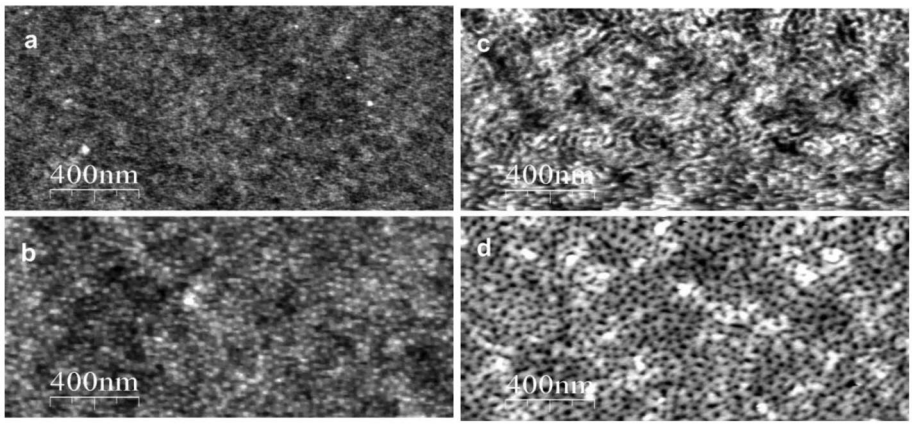


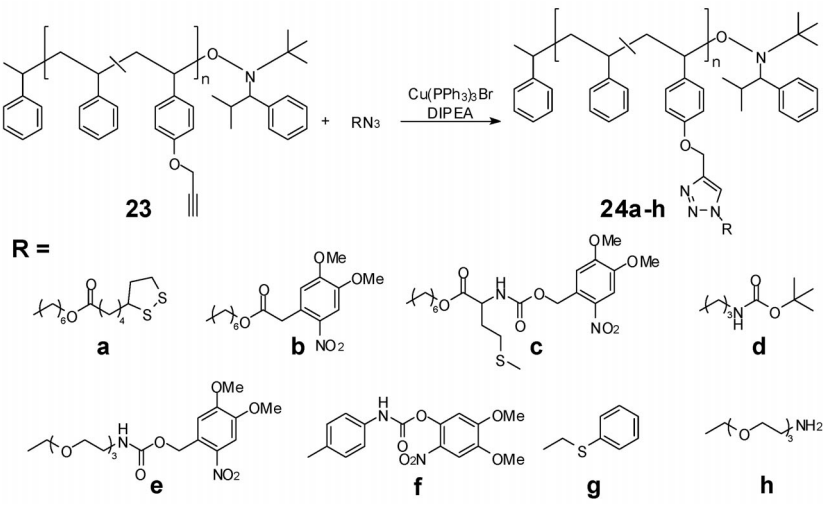
Fig. 1 AFM phase images of linear-dendronized diblock copolymer thin films. (a) precursor diblock copolymer **9b**, (b) **9b-G1**, (c) **9b-G2**, (d) **9b-G3** [57].

As expected, the precursor diblock copolymer **9b** shows no phase separation (Fig. 1a) and a flat homogeneous surface was observed, while the dendronized block copolymer phase separated strongly (Figs. 1b–d). However, the morphology greatly depends on the generation of the attached dendrons. Dendronized diblock copolymer **9b-G1** (Fig. 1b) builds spherical domains, which are formed by the dendronized blocks, whereas the linear block constitutes the matrix. The dendritic block occupies more and more space with increasing generation of the dendron, so the dendronized diblock copolymer **9b-G2** (Fig. 1c) forms a lamellar morphology. The film of dendronized diblock copolymer **9b-G3** (Fig. 1d) shows also a spherical morphology similar to the film of **9b-G1**, with the difference that the dendritic block constitutes the matrix and the linear block builds holes.

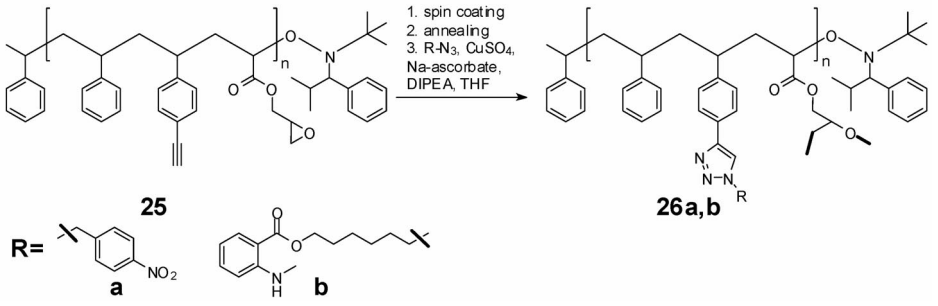
Our first approach with regard to attaching polymer thin films to surfaces for further wet chemical modification [59] addressed functional polymers adequate for surface patterning onto gold substrates. For this, a random copolymer based on styrene and acetoxystyrene was synthesized by NMRP. This polymer was modified by hydrolysis of the acetyl group and subsequent reaction with propargyl bromide to get an alkyne-containing polymer (**23**), which is clickable in a 1,3-dipolar cycloaddition.

The postmodification of the polymer **23** was performed with different functional azides (Scheme 10). Azide **a** carries a sulfide group for anchoring onto gold substrates, the azides **b**, **c**, **e**, and **f** incorporate a photolabile protecting group for patterning applications. The freed amino groups in **b**, **e**, and **f** can be used for attachment of gold colloids or nanoelements like DNA strands, the amino group in **c** is part of an amino acid derivative and the methyl sulfide moiety is also an anchoring group onto gold. The *tert*-butyloxycarbonyl (^{t}BOC) group in **d** is also a protective group for the amino group, which can be removed after irradiation in the presence of a photoacid generator. Azide **g** contains another anchoring group, and azide **h** supplies directly the free amino functionality. The obtained polymers were characterized by combination of spectroscopic and chromatographic methods. In most cases, the polydispersity indexes (PDIs) increased minimally after polymer analogous reaction, only in the case of polymer **24a**, **c**, and **e**, PDIs above 1.3 were observed. This may be explained by complexation of the Cu catalyst to the disulfide as well as a Glaser analogous coupling reaction between two alkynes.

Subsequently, we demonstrated the efficient postmodification of a polymeric surface by click chemistry [60]. A novel well-defined alkyne-containing terpolymer (**25**) was developed that was prone



Scheme 10 Postmodified polymers by click reaction with functional azides suitable for thin film anchoring and functionalization [59].



Scheme 11 Polymers used for covalent attachment onto surfaces and subsequent polymer analogous click reaction [60].

to be tethered onto Si substrates by glycidyl methacrylate moieties. This polymer was spin-coated on Si wafers with subsequent annealing at 140 °C in vacuum to anchor the glycidyl groups on the silanol groups of the surface (Scheme 11). The tethered polymer films were reacted with two different azides in a click reaction. IR-ellipsometry measurements showed the successful conversion because of the absence of the alkyne band at 3296 and 2105 cm^{-1} after solvent extraction. Furthermore, the same procedure was carried out onto quartz substrates with the fluorescent dye containing azide **b**. The fluorescent spectra show after a third tetrahydrofuran (THF) washing a constant fluorescence intensity indicating a chemical binding of the dye.

Taking into account our previous results [59], we investigated the synthesis of block copolymers by RAFT polymerization with subsequent polymer analogous reaction to introduce anchor as well as photolabile protected groups [44,61]. These polymers can possibly be applied in subsequent site-specific deposition of charged nanoparticles or biomolecules like DNA or proteins [62,63]. Figure 2a shows the structure of the block copolymer (**27**), which was synthesized by RAFT polymerization as well as two polymer analogous reactions. The precursor block copolymer consists of a poly(styrene-*co*-4-chloromethylstyrene) and a poly(styrene-*co*-4-propargyloxystyrene) block. In a first step, the functional unit 6-nitroveratryl 2-azidoethylcarbamate, which includes the photolabile protecting group, was introduced by click chemistry. In a second step, the anchor group for Au substrates was integrated by a

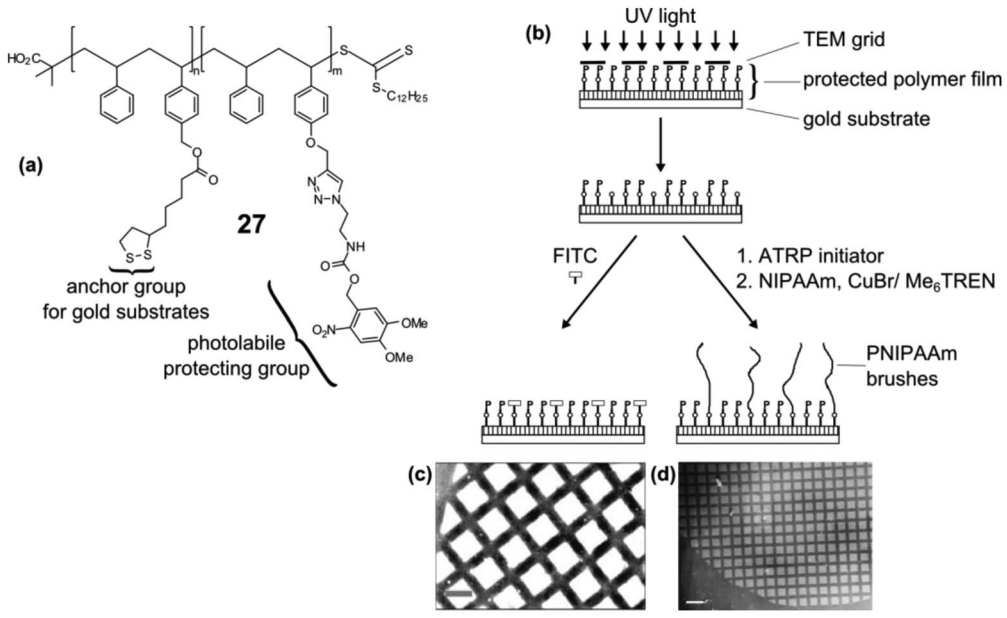


Fig. 2 (a) Block copolymer (**27**) with anchor group for Au substrates and photolabile protecting group, (b) illustration of UV irradiation of the polymer film with subsequent binding of FITC as well as ATRP initiator to the released amino groups. In the case of the ATRP initiator, a surface initiation of the ATRP of NIPAAm is followed, (c) fluorescence microscopy image of the FITC modified film (scale bar: 40 μm), (d) SEM image of modified film by PNIPAAm brushes (scale bar: 100 μm) [44].

reaction of the benzyl chloride groups with lipoic acid in the presence of Cs carbonate. Both polymer analogous reactions gave high conversions and showed no appreciable side-reactions.

To demonstrate the photopatterning, this polymer was spin-coated on Au substrates. By the disulfide function the polymer film was attached tightly on the substrate. After intensive washing, the film was irradiated through a transmission electron microscopy (TEM) grid by UV light, which cleaved the NVOC-protecting groups released free amino functions on the exposed parts (Fig. 2b, first step).

After that, two approaches were introduced to modify the surface. In a first one, the film was immersed into a solution of fluorescein isothiocyanate (FITC), which is a model compound for the often used attachment of biomacromolecules onto amino-functionalized surfaces through isothiocyanate linker. Figure 2c shows the fluorescence microscopy image. The second approach was to bind an ATRP initiator (2-bromoisobutyryl bromide) on the released amino functions. The exposure of these films to ATRP conditions in the presence of the monomer NIPAAm led to the formation of polymer brushes on the irradiated areas. Figure 2d shows the scanning electron microscopy (SEM) image of the modified film with the PNIPAAm brushes.

A further step was now the construction of block copolymers, which can not only photopattern but also show a phase separation. So a combination of "top-down" with "bottom-up" approaches becomes possible. We synthesized various block copolymers by RAFT polymerization [64,65], which are able to form nanostructures (Fig. 4). The block copolymers consist of a polar block based on methacrylate derivatives or vinylpyridine and of an unpolar block based on styrene derivatives. The integration of cross-linking groups (vinylpyridine (**29**) and hydroxystyrene (**30**) groups) enables the stabilization of the nanostructures of the thin films [66–68]. In order to get multifunctional block copolymer films, the insertion of further functionalities was necessary. One functionality was again the alkyne group (**31**, **32**), which can be modified by the click reaction, for example, with a photolabile protecting group similar to [44] before film formation or directly on the surface bound polymer film [60] (Fig. 3).

Another interesting functionality, which was introduced into block copolymers, was the pentafluorostyrene group (**28–30**), which promotes phase separation on the one hand due to high hydrophobicity and on the other hand is suitable for effective polymer analogous reaction [64,69,70] (Scheme 12).

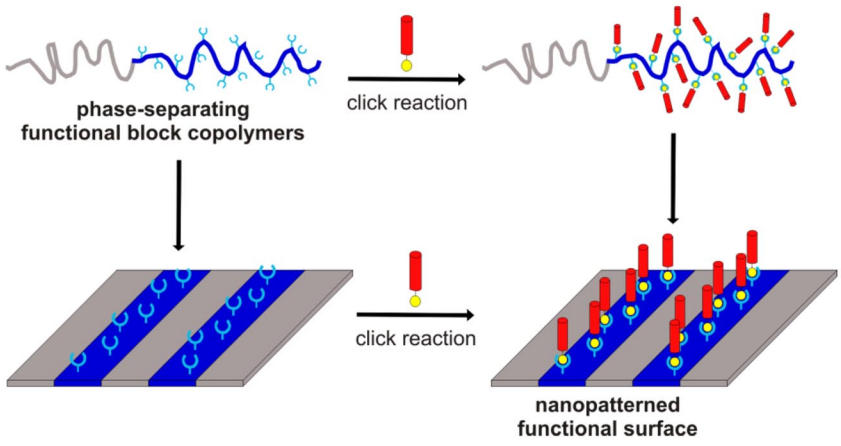
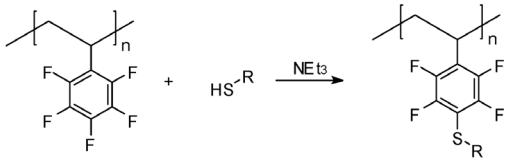


Fig. 3 Illustration of modification of a functional block copolymer either before film formation or directly on the surface-bound polymer film.



Scheme 12 Polymer analogous reaction of the pentafluorostyrene group with a thiol group.

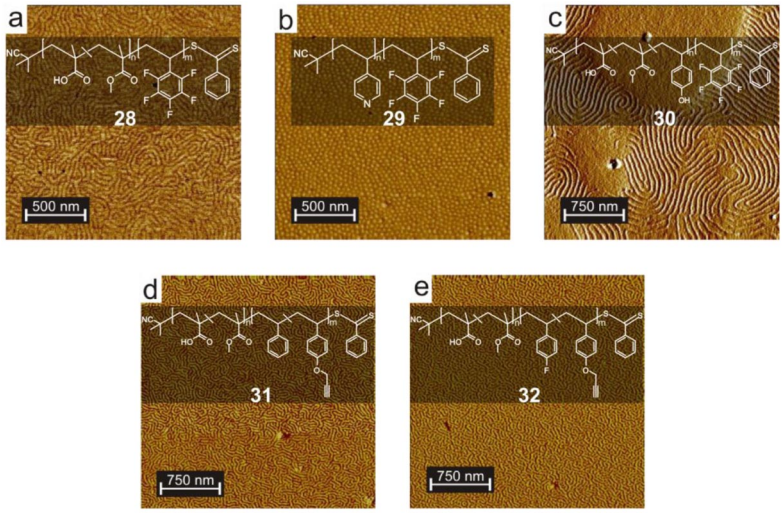
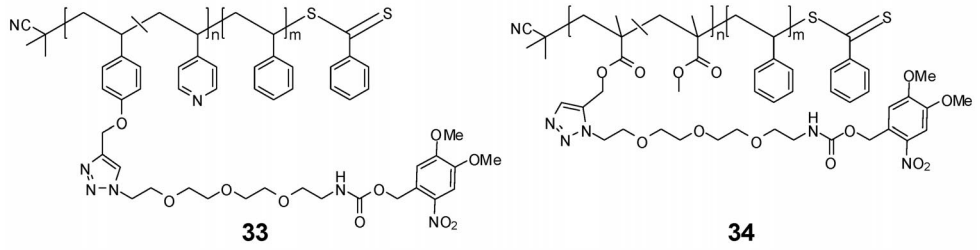


Fig. 4 Structures of the various phase-separating block copolymers with the corresponding AFM phase images of thin films prepared from them.

The AFM phase images (Fig. 4) of the five block copolymers show for each case nanostructure formation by phase separation. All block copolymers with the exception of **29** form thin film structures assembled by laying down cylinders. The film of block copolymer **29** is formed by standing cylinders, which appear as dots in the matrix.

Block copolymer examples [71] where photolabile protecting groups were inserted by click reactions are shown in Scheme 13. These polymers form nanostructures in thin films and can be used for lithographic photopatterning with a subsequent further modification of the surface. Thus, hybrid patterning, meaning the combination of nanostructuring by phase separation combined with lithographic patterning on the microscale, becomes accessible.



Scheme 13 Photopatternable and phase-separating block copolymers [71].

CONCLUSION

The use of CRP techniques in combination with "click chemistry" in the polymer synthesis significantly broadened the scope of functional polymer materials in the last decade. A large variety of complex polymer architectures becomes available through the high control of molar mass and end-groups provided by the CRP methods, and these can now be combined with various sensitive functionalities, which cannot be introduced by direct polymerization. In addition, nanostructure formation achieved by self-assembly in solution or in thin films can now be combined with precise introduction of functionality promoting significantly the use of soft matter in demanding application like catalysis, biomedicine, diagnostics, and macro- and nanoelectronics.

We see special further chances by combining nanostructure formation in thin polymer film though self-assembly of block copolymers with patterning with functional groups on the nanoscale as well as the combination of lithographic methods (top-down) and bottom-up approaches. Microsystem technology used in diagnostics and biochips as well as in actuators and the nanoelectronic area can especially profit significantly from multifunctional polymer materials specially designed for that purpose.

ACKNOWLEDGMENTS

The partial financial support of the work by the Saxon State Excellence Initiative European Centre for Emerging Materials and Processes (ECEMP) and the European Regional Development Fund (ERDF) is gratefully acknowledged.

REFERENCES

1. C. J. Hawker, A. W. Bosman, E. Harth. *Chem. Rev.* **101**, 3661 (2001).
2. C. Barner-Kowollik, S. Perrier. *J. Polym. Sci., Part A: Polym. Chem.* **46**, 5715 (2008).
3. G. Moad, E. Rizzardo, S. H. Thang. *Polymer* **49**, 1079 (2008).
4. N. V. Tsarevsky, K. Matyjaszewski. *Chem. Rev.* **107**, 2270 (2007).
5. H. C. Kolb, M. G. Finn, K. B. Sharpless. *Angew. Chem., Int. Ed.* **40**, 2004 (2001).

6. R. K. Iha, K. L. Wooley, A. M. Nystrom, D. J. Burke, M. J. Kade, C. J. Hawker. *Chem. Rev.* **109**, 5620 (2009).
7. C. Barner-Kowollik, F. E. Du Prez, P. Espeel, C. J. Hawker, T. Junkers, H. Schlaad, W. Van Camp. *Angew. Chem., Int. Ed.* **50**, 60 (2011).
8. C. Barner-Kowollik, A. J. Inglis. *Macromol. Chem. Phys.* **210**, 987 (2009).
9. C. R. Becer, R. Hoogenboom, U. S. Schubert. *Angew. Chem., Int. Ed.* **48**, 4900 (2009).
10. W. H. Binder, R. Sachsenhofer. *Macromol. Rapid Commun.* **29**, 952 (2008).
11. D. Fournier, R. Hoogenboom, U. S. Schubert. *Chem. Soc. Rev.* **36**, 1369 (2007).
12. P. L. Golas, K. Matyjaszewski. *Chem. Soc. Rev.* **39**, 1338 (2010).
13. C. J. Hawker, V. V. Fokin, M. G. Finn, K. B. Sharpless. *Aust. J. Chem.* **60**, 381 (2007).
14. C. J. Hawker, K. L. Wooley. *Science* **309**, 1200 (2005).
15. A. J. Inglis, C. Barner-Kowollik. *Macromol. Rapid Commun.* **31**, 1247 (2010).
16. J. F. Lutz, H. Schlaad. *Polymer* **49**, 817 (2008).
17. B. S. Sumerlin, A. P. Vogt. *Macromolecules* **43**, 1 (2010).
18. A. Gregory, M. H. Stenzel. *Prog. Polym. Sci.* **37**, 38 (2012).
19. N. Akeroyd, B. Klumperman. *Eur. Polym. J.* **47**, 1207 (2011).
20. A. B. Lowe. *Polym. Chem.* **1**, 17 (2010).
21. M. Meldal, C. W. Tornoe. *Chem. Rev.* **108**, 2952 (2008).
22. D. D. Diaz, S. Punna, P. Holzer, A. K. Mcpherson, K. B. Sharpless, V. V. Fokin, M. G. Finn. *J. Polym. Sci., Part A: Polym. Chem.* **42**, 4392 (2004).
23. P. Wu, A. K. Feldman, A. K. Nugent, C. J. Hawker, A. Scheel, B. Voit, J. Pyun, J. M. J. Frechet, K. B. Sharpless, V. V. Fokin. *Angew. Chem., Int. Ed.* **43**, 3928 (2004).
24. S. R. S. Ting, A. M. Granville, D. Quemener, T. P. Davis, M. H. Stenzel, C. Barner-Kowollik. *Aust. J. Chem.* **60**, 405 (2007).
25. D. Quemener, M. Le Hellaye, C. Bissett, T. P. Davis, C. Barner-Kowollik, M. H. Stenzel. *J. Polym. Sci., Part A: Polym. Chem.* **46**, 155 (2008).
26. B. Helms, J. L. Mynar, C. J. Hawker, J. M. J. Frechet. *J. Am. Chem. Soc.* **126**, 15020 (2004).
27. J. Kumar, A. Bousquet, M. H. Stenzel. *Macromol. Rapid Commun.* **32**, 1620 (2011).
28. T. Trellenkamp, H. Ritter. *Macromolecules* **43**, 5538 (2010).
29. M. Malkoch, R. J. Thibault, E. Drockenmuller, M. Messerschmidt, B. Voit, T. P. Russell, C. J. Hawker. *J. Am. Chem. Soc.* **127**, 14942 (2005).
30. B. Voit. *New J. Chem.* **31**, 1139 (2007).
31. H. Zhao, W. Y. Gu, E. Sterner, T. P. Russell, E. B. Coughlin, P. Theato. *Macromolecules* **44**, 6433 (2011).
32. J. M. Spruell, M. Wolffs, F. A. Leibfarth, B. C. Stahl, J. H. Heo, L. A. Connal, J. Hu, C. J. Hawker. *J. Am. Chem. Soc.* **133**, 16698 (2011).
33. H. C. Kim, S. M. Park, W. D. Hinsberg. *Chem. Rev.* **110**, 146 (2010).
34. O. Bertrand, J. M. Schumers, C. Kuppan, J. Marchand-Brynaert, C. A. Fustin, J. F. Gohy. *Soft Matter* **7**, 6891 (2011).
35. M. Shokeen, E. D. Pressly, A. Hagooly, A. Zheleznyak, N. Ramos, A. L. Fiamengo, M. J. Welch, C. J. Hawker, C. J. Anderson. *ACS Nano* **5**, 738 (2011).
36. G. W. Goodall, W. Hayes. *Chem. Soc. Rev.* **35**, 280 (2006).
37. S. Fleischmann, H. Komber, B. Voit. *Macromolecules* **41**, 5255 (2008).
38. M. Heuken, H. Komber, B. Voit. *Macromol. Chem. Phys.* **213**, 97 (2012).
39. M. Heuken, H. Komber, T. Erdmann, V. Senkovskyy, A. Kiriy, B. Voit. *Macromolecules* **45**, 4101 (2012).
40. W. H. Kruizinga, B. Strijtveen, R. M. Kellogg. *J. Org. Chem.* **46**, 4321 (1981).
41. S. S. Wang, B. F. Gisin, D. P. Winter, R. Makofske, I. D. Kulesha, C. Tzougraki, J. Meienhofer. *J. Org. Chem.* **42**, 1286 (1977).
42. G. Dijkstra, W. H. Kruizinga, R. M. Kellogg. *J. Org. Chem.* **52**, 4230 (1987).

43. J. A. Cella, S. W. Bacon. *J. Org. Chem.* **49**, 1122 (1984).
44. J. Stadermann, M. Erber, H. Komber, J. Brandt, K. J. Eichhorn, M. Bonsch, M. Mertig, B. Voit. *Macromolecules* **43**, 3136 (2010).
45. E. Kaul, V. Senkovskyy, R. Tkachov, V. Bocharova, H. Komber, M. Stamm, A. Kiriy. *Macromolecules* **43**, 77 (2010).
46. R. Vukicevic, U. Schwadtke, S. Schmucker, P. Schafer, D. Kuckling, S. Beuermann. *Polym. Chem.* **3**, 409 (2012).
47. P. J. Roth, C. Boyer, A. B. Lowe, T. P. Davis. *Macromol. Rapid Commun.* **32**, 1123 (2011).
48. M. M. Stamenovic, P. Espeel, W. Van Camp, F. E. Du Prez. *Macromolecules* **44**, 5619 (2011).
49. J. Sun, H. Schlaad. *Macromolecules* **43**, 4445 (2010).
50. S. Fleischmann, H. Kornber, D. Appelhans, B. I. Voit. *Macromol. Chem. Phys.* **208**, 1050 (2007).
51. J. Dao, D. Benoit, C. J. Hawker. *J. Polym. Sci., Part A: Polym. Chem.* **36**, 2161 (1998).
52. P. M. Fresneda, P. Molina. *Synlett* 1 (2004).
53. R. Pötzsch, S. Fleischmann, C. Tock, H. Komber, B. I. Voit. *Macromolecules* **44**, 3260 (2011).
54. J. Stadermann, H. Komber, M. Erber, F. Dabritz, H. Ritter, B. Voit. *Macromolecules* **44**, 3250 (2011).
55. M. J. Kade, D. J. Burke, C. J. Hawker. *J. Polym. Sci., Part A: Polym. Chem.* **48**, 743 (2010).
56. E. Soto-Cantu, B. S. Lokitz, J. P. Hinestrosa, C. Deodhar, J. M. Messman, J. F. Ankner, S. M. Kilbey Ii. *Langmuir* **27**, 5986 (2011).
57. S. Fleischmann, A. Kiriy, V. Bocharova, C. Tock, H. Komber, B. Voit. *Macromol. Rapid Commun.* **30**, 1457 (2009).
58. M. Malkoch, K. Schleicher, E. Drockenmuller, C. J. Hawker, T. P. Russell, P. Wu, V. V. Fokin. *Macromolecules* **38**, 3663 (2005).
59. B. Sieczkowska, M. Millaruelo, M. Messerschmidt, B. Voit. *Macromolecules* **40**, 2361 (2007).
60. S. Fleischmann, K. Hinrichs, U. Oertel, S. Reichelt, K. J. Eichhorn, B. Voit. *Macromol. Rapid Commun.* **29**, 1177 (2008).
61. J. Stadermann, S. Fleischmann, M. Messerschmidt, H. Komber, B. Voit. *Macromol. Symp.* **275–276**, 35 (2009).
62. M. Millaruelo, L. M. Eng, M. Mertig, B. Pilch, U. Oertel, J. Opitz, B. Sieczkowska, F. Simon, B. Voit. *Langmuir* **22**, 9446 (2006).
63. J. Opitz, F. Braun, R. Seidel, W. Pompe, B. Voit, M. Mertig. *Nanotechnology* **15**, 717 (2004).
64. M. Riedel, J. Stadermann, H. Komber, F. Simon, B. Voit. *Eur. Polym. J.* **47**, 675 (2011).
65. J. Stadermann, M. Riedel, H. Komber, F. Simon, B. Voit. *J. Polym. Sci., Part A: Polym. Chem.* **50**, 1351 (2012).
66. P. Du, M. Q. Li, K. Douki, X. F. Li, C. R. W. Garcia, A. Jain, D. M. Smilgies, L. J. Fetters, S. M. Gruner, U. Wiesner, C. K. Ober. *Adv. Mater.* **16**, 953 (2004).
67. K. Ishizu, T. Ikemoto, A. Ichimura. *Polymer* **40**, 3147 (1999).
68. Y. M. Lam, L. X. Song, Y. C. Moy, L. F. Xi, C. Boothroyd. *J. Colloid Interface Sci.* **317**, 255 (2008).
69. C. R. Becer, K. Babiuch, D. Pilz, S. Hornig, T. Heinze, M. Gottschaldt, U. S. Schubert. *Macromolecules* **42**, 2387 (2009).
70. C. Ott, R. Hoogenboom, U. S. Schubert. *Chem. Commun.* 3516 (2008).
71. J. Stadermann. In *Faculty of Science*. Technischen Universität Dresden, Dresden (2010).

