

Summary

This thesis describes the use of multivalent host-guest interactions at interfaces for the construction of 2D and 3D nanostructures. Self-assembled monolayers (SAMs) on flat surfaces and nanoparticles have been employed to confine and organize such structures. The host-guest interactions between β -cyclodextrin (CD) and different guest derivatives are the focus of attention in this thesis. Host monolayers of CDs were prepared on flat gold and silicon oxide surfaces. These host monolayers have been utilized as molecular printboards for the recognition and positioning of molecules by means of multiple supramolecular interactions. Gold nanoparticles have also been modified with CD and the formation of large 3D aggregates in the presence of multivalent guest molecules was studied as a function of the number of hydrophobic endgroups of the guest molecule and its geometry. The combination of multiple interactions between adamantyl-terminated dendrimers and CD-modified gold nanoparticles (CD Au NPs) was employed to create organized 2D structures at surfaces generated by layer-by-layer assembly. The combination with lithographic techniques, by which such structures can be directed to specific target areas, led to the formation of 3D nanostructures.

New methodologies for the assembly of molecular- to micrometer-scale objects onto substrates in predetermined arrangements for the fabrication of 2D and 3D nanostructures are reviewed in Chapter 2. The positioning of molecules onto substrates has been achieved with noncovalent interactions, with special attention to multiple supramolecular interactions for the assembly. The first part of this chapter covers different systems and methodologies that have been used in order to attach molecules and nanoparticles to flat surfaces. Some examples of layer-by-layer systems are described as potential platforms for the construction of 3D systems, especially when combined with patterning methodologies. The second section is focused on various methodologies to create and control nanoparticle assembly into well-defined nanoarchitectures.

Chapter 3 describes the interaction between poly(isobutene-*alt*-maleic acid)s modified with *p*-*tert*-butylphenyl or adamantyl groups and CD SAMs. The binding of the hydrophobic guest-functionalized polymers to the CD SAMs takes place through multiple inclusions of the guest substituents of the polymers into the CD cavities. It was shown to be very strong and irreversible. In solution these polymers are known to be spherical with a hydrodynamic radius of about 10 nm. They have strong intramolecular hydrophobic interactions leading to reduce affinity for CD in solution. However, the polymer adsorption onto the CD SAMs led to very thin polymer films (0.5 nm) as shown by AFM scratching experiments. Apparently the polymer uses all or many of the hydrophobic groups, as was further supported by the absence of specific binding of CD Au NPs to the polymer surface assemblies. Variations of the nature and/or number of hydrophobic groups in the polymer, and of the polymer concentration in solution did not lead to significant differences in adsorption behavior. Competition experiments with monovalent host and guest, did not lead to measurable polymer desorption. This behavior was attributed to the large number of functional groups on the polymer and to the close-to-optimal linker lengths (1.6-5.4 nm) between the hydrophobic substituents, leading to high effective concentrations (0.25 M) and thus very high estimated binding constants ($K > 5 \times 10^{87} \text{ M}^{-1}$). Supramolecular microcontact printing (μ CP) of the polymers onto the CD SAMs resulted in the assembly formation in the targeted areas of the substrate.

Chapter 4 shows that adamantyl-terminated guest molecules can mediate the aggregation of CD Au NPs in aqueous solution by employing strong and specific, multivalent host-guest interactions. Gold nanoparticles bearing surface-immobilized CD hosts were synthesized following a one-phase procedure and characterized by UV-vis spectroscopy, thermogravimetric analysis, ^1H NMR spectroscopy and TEM. The latter showed unaggregated particles and a relatively narrow particle size distribution of 2.8 ± 0.6 nm. The aggregation rate between the CD Au NPs and the guest molecules could be controlled taking into account several parameters such as, the number of interactions available for the assembly, the geometry of the molecules and the addition of a competitor in solution to prevent aggregation. Adamantyl-terminated dendrimers, owing to their globular shape and high number of interactions, led to the formation of insoluble nanoparticle aggregates without a long-range order, which is a strong indication of

intermolecular binding. Conversely, a bis-adamantyl molecule, with two interaction sites and a flexible linker did not show the formation of an insoluble complex, which was attributed to predominantly *intramolecular* binding. Addition of the monovalent adamantyl carboxylate to a solution of CD Au NPs did not induce precipitation and resulted in stable assemblies. The binding constant ($2.31 \times 10^4 \text{ M}^{-1}$) could be determined by isothermal titration calorimetry (ITC). In contrast to the experiments using CD Au NPs, the addition of adamantyl-terminated dendrimers to a solution of oligo(ethylene glycol)-functionalized Au NPs did not lead to precipitation nor to changes of the plasmon absorption band. Furthermore, by adding a monovalent competitor in solution, the aggregation process of the bis-adamantyl guest molecule could be controlled.

Chapter 5 describes a new supramolecular procedure for the stepwise construction of a novel kind of self-assembled organic/inorganic multilayer thin films. The procedure is based on the layer-by-layer (LBL) assembly of guest-functionalized dendrimers and CD Au NPs deposited onto CD SAMs on gold or on SiO_2 . This type of supramolecular LBL assembly was demonstrated to yield multilayer thin films with a thickness control at the nm level. Different techniques were used to monitor the assembly. Surface plasmon resonance spectroscopy (SPR) was used to monitor in situ the LBL assembly at different concentrations of the components. The adsorption behavior was observed to be similar at the studied range of concentrations, showing a linear growth with the number of bilayers deposited onto the CD SAMs. Blank experiments lacking the host SAM or the guest molecule did not show any specific or controllable LBL assembly. Information about the absolute thickness increase with the number of bilayers was obtained from ellipsometry and AFM. An estimate of the multilayer thickness of 2 nm/bilayer was obtained in both cases. Furthermore, UV/vis spectroscopy was used to monitor the supramolecular assembly on a glass surface. The linear increase in absorption at 525 nm as a function of the number of bilayers (for 1-18 bilayers) was again a strong indication of a well-defined deposition process. Additionally, UV/vis spectroscopy gave a quantitative estimation of the amount of material deposited after each cycle assuming a hexagonal packing of monodisperse particles. Comparison between the experimental and the theoretical values clearly indicates that close to a monolayer of CD Au NPs was deposited after each assembly cycle.

Chapter 6 introduces various patterning strategies to create 3D hybrid nanostructures of dendrimers and CD Au NPs on CD SAMs based on multiple supramolecular interactions using the LBL approach described in Chapter 5. Initially, μ CP and nanoimprint lithography (NIL), followed by metal evaporation and lift-off, have been performed in order to obtain chemically patterned SAMs to attempt directed LBL assembly, relying on the supramolecular specificity. However, these two approaches did not result in patterned LBL assemblies, and indiscriminate multilayer deposition was observed attributed to nonspecific adsorption of the dendrimers. In contrast, nanotransfer printing (nTP) and NIL resulted in patterned LBL assemblies on the CD SAMs. nTP was achieved by LBL assembly on an oxidized PDMS stamp followed by transfer onto a full CD SAM. The structures showed good stability against rinsing, even with a monovalent, competitive host in solution, and against acetone/ultrasound treatment. nTP-patterned LBL assemblies showed a linear thickness increase of approx. 3 nm per bilayer. The supramolecular specificity observed was not perfect which could again be attributed to nonspecific interactions of the dendrimers. Furthermore, LBL assemblies patterned by NIL, LBL assembly, and lift-off have been obtained using PMMA as a physical barrier for the multilayer deposition. Thus, patterned LBL assemblies showed a linear thickness increase, in this case of only about 1.1 nm per bilayer. These differences in the multilayer heights as a function of the number of bilayers can possibly be explained by wetting problems. Nevertheless, high resolution 3D nanostructures with aspect ratios on the order of 1 were obtained combining LBL assembly and NIL.

Chapter 7 introduces a new concept for nanofabrication which involves multivalent, heterotropic, orthogonal interactions. The binding of a host-guest metal-ligand complex formed between adamantyl-functionalized ethylenediamine (L) and Cu(II) or Ni(II) at CD SAMs was shown to result from multivalency of the guest molecules. To verify the orthogonality of the metal-ethylenediamine and CD-adamantyl binding motifs, binding studies of L, with or without Cu(II) at various pH, with CD were performed in aqueous solution using ITC. The binding constants with ($K = 7.9 \times 10^4 \text{ M}^{-1}$) and without ($K = 6.0 \times 10^4 \text{ M}^{-1}$) Cu(II) are typical for a 1:1 CD-adamantyl inclusion interaction and showed no influence of pH on the complexation, thus proving full orthogonality. Binding constants at CD SAMs were of the same order of magnitude as in

solution. Quantitative analysis of the different species present in solution and at the surface was performed as a function of pH by using a sequential, multivalent, heterotropic binding model. At high pH the metal complex adsorption on the surface led to the preferred formation of the divalent form (CuL_2), while at pH 5 mainly the monovalent species were present. The same behavior was observed in solution. Conversely, at pH 6 the multivalent surface clearly enhanced the presence of the divalent CuL_2 complex at its interface with an enhancement factor (EF) higher than 100, whereas monovalent species were predominant in solution. This behavior is attributed to the high effective concentration of CD sites present at the surface and the close-to-optimal linker lengths between the two adamantyl groups relative to the periodicity of the CD lattice (ca. 2 nm). In the case of the Ni(II) complex, the sequential multivalent, heterotropic binding model could not discriminate between divalent or trivalent binding. Desorption experiments, performed at equal concentrations, showed comparable desorption rates for both Ni(II) and Cu(II) complexes, which is a strong indication of divalent binding at the surface in both cases. Quantitative analysis of the different species of the Ni(II) complexes showed that the divalent form was hardly present in solution but multivalency enhanced its presence at the surface, again with $EF > 100$.

The results presented in this thesis illustrate the versatility of self-assembly and multivalency to create 2D and 3D nanostructures and to apply such protocols in more complex nanofabrication schemes. The work on the different supramolecular assemblies on flat surfaces and nanoparticles demonstrates that different nanoarchitectures can be obtained by combining the supramolecular specificity and stability of multiple interactions. Combination with lithographic techniques, such as μCP and NIL, opens new approaches for the supramolecular patterning of interfaces and for the construction of well-defined 3D nanostructures.