

Writing with molecules on molecular printboards†

Olga Crespo-Biel, Bart Jan Ravoo, Jurriaan Huskens and David N. Reinhoudt*

Received 13th December 2005, Accepted 8th February 2006

First published as an Advance Article on the web 2nd May 2006

DOI: 10.1039/b517699a

Nanotechnology aspires to create functional materials with characteristic dimensions of the order 1–100 nm. One requirement to make nanotechnology work is to precisely position molecules and nanoparticles on surfaces, so that they may be addressed and manipulated for bottom-up construction of nanoscale devices. Here we review the concept of a “molecular printboard”. A molecular printboard is a monolayer of host molecules on a solid substrate on which guest molecules can be attached with control over position, binding strength, and binding dynamics. To this end, cyclodextrins were immobilized in monomolecular layers on gold, on silicon wafers and on glass. Guest molecules (for example, adamantane and ferrocene derivatives) bind to these host surfaces through supramolecular, hydrophobic inclusion interaction. Multivalent interactions are exploited to tune the binding strength and dynamics of the interaction of guest molecules with the printboard. Molecules can be positioned onto the printboard using supramolecular microcontact printing and supramolecular dip-pen nanolithography due to the specific interaction between the ‘ink’ and the substrate. In this way, nanoscale patterns can be written and erased on the printboard. Currently, the molecular printboard is exploited for nanofabrication, for example in combination with electroless deposition of metals and by means of supramolecular layer-by-layer deposition.

Introduction

At first sight, nanotechnology is nothing more than the logical extension of microtechnology: a step further toward miniaturization.^{1,2} Nanoscience and nanotechnology deal with individual objects with dimensions between 1 and 100 nm. In physics, such objects are considered to be small, in chemistry they are considered to be large, while for biologists this is the usual size of individual biomacromolecules. However, not only would nanotechnology reduce the dimensions of existing microdevices, but more importantly it produces objects and materials with fundamentally novel properties. The expectations of what nanotechnology will achieve in the future range from quantum computers, ultrastrong materials, self-cleaning fabrics, and information storage and retrieval, to drug delivery to individual cells and implantable biosensors.³

There are two fundamentally different ways of fabricating nanostructures: top-down and bottom-up. The top-down technologies are usually an extrapolation of existing physical methods, such as lithography with electron or ion beams that have much smaller wavelengths than visible or UV light. Novel top-down technologies use sharp STM or AFM tips to write patterns by scratching, local deposition of material, or even writing with (bio)molecules. Recently, technologies that are very familiar to chemists, like printing and writing, have emerged (in the forms of soft lithography and nanoimprint lithography) as potential competitors for photolithography.^{4,5}

Self-assembly is the alternative bottom-up approach, which uses individual molecules as the building blocks and supramolecular chemistry to assemble these into larger structures. Self-assembly also appears as a strategy for merging bottom-up and top-down fabrication, leading to hierarchical structures of types so widely found in Nature.

Self-assembled monolayers: a molecular printboard

Positioning of molecules on surfaces is essential in nanofabrication, where a key challenge is whether individual units, such as small and large molecules, proteins and nanoparticles can be positioned with nanometer precision. Supramolecular interactions, such as those observed in host–guest complexes, are specific and directional, and a wealth of information is usually available on their binding strengths and kinetics. Moreover, the application of molecules that allow multiple supramolecular interactions provides a tool to tune adsorption and desorption because the thermodynamic and kinetic parameters are related to the number of interactions as well as the strength and the kinetics of an individual interaction.

A single ordered layer of molecules anchored on a surface can be used as platform because, in principle, its orientation and positioning can be controlled, producing well defined structural motifs organized over large areas in two dimensions. Self-assembled monolayers (SAMs)⁶ are ordered molecular assemblies formed by the adsorption of an adsorbate on a solid surface. The order of these SAMs relies on the spontaneous chemisorption at the interface, as the system approaches equilibrium. The versatility and flexibility, both at the individual molecular and at the materials levels, renders SAMs as a valuable substrate for the production of two-dimensional (2D) and three-dimensional (3D) assemblies.

Laboratory for Supramolecular Chemistry and Technology, MESA⁺ Institute for Nanotechnology, University of Twente, P. O. Box 217, 7500 AE, Enschede, The Netherlands. E-mail: d.n.reinhoudt@utwente.nl

† Based on the presentation given at Dalton Discussion No. 9, 19–21st April 2006, Hulme Hall, Manchester, UK.

Olga Crespo Biel (1978) studied chemistry at the Universitat Autònoma de Barcelona (Spain) from 1996 until 2001. From October 2000 to March 2001 she was an Erasmus student in the group of Catalytic Processes and Materials at the University of Twente. In November 2001 she returned to Twente and joined the Supramolecular Chemistry and Technology group directed by Prof. D. N. Reinhoudt, where she worked as a PhD student under the supervision of Prof. J. Huskens and Dr B. J. Ravoo. At present she is working as a postdoctoral researcher in the department of Performance Materials Chemistry and Technology at DSM Research (The Netherlands).

Bart Jan Ravoo (1970) obtained his graduate and postgraduate degrees in chemistry from the University of Groningen, The Netherlands. In 1999 he moved to University College Dublin, Ireland where he held a Newman Scholarship for a period of three years. In 2002 he was appointed as assistant professor at the University of Twente. His main research interest is self-assembly and molecular recognition in water and at the dynamic interface between water and (soft) surfaces. His research includes the development of functional SAMs, soft lithography and nanofabrication.

Jurriaan Huskens (1968) studied chemical engineering at the Eindhoven University of Technology and obtained his PhD from the Delft University of Technology in 1994. In 1995 and 1996, he was a postdoc with Prof. Sherry at the University of Texas at Dallas, USA. In 1997, he was awarded a Marie Curie fellowship to work in the group of Prof. Reetz at the Max-Planck-Institut für Kohlenforschung, Mülheim an der Ruhr, Germany. In 1998, he became an assistant professor in the group of Prof. Reinhoudt. In 2005 he was appointed as program director "NanoFabrication" of the MESA+ Institute for Nanotechnology and soon after as full professor of Molecular Nanofabrication at the University of Twente.

David N. Reinhoudt was born in 1942 in The Netherlands and obtained a PhD in chemistry in Delft in 1969. From 1970 to 1975 he worked at Shell on the crown ether research program. He was appointed as a part-time professor at the University of Twente in 1975 and as a full professor in 1978. Nowadays he is in charge of the Laboratory of Supramolecular Chemistry and Technology, scientific director of the MESA+ Institute for Nanotechnology, and chairman of the Board of NanoNed, the Dutch program for Nanotechnology. He is the author of more than 800 scientific publications and patents.



Olga Crespo-Biel



Jan Ravoo



Jurriaan Huskens



David N. Reinhoudt

In our laboratory we have previously prepared SAMs of molecular receptors such as resorcin[*n*]arene derivatives and cyclodextrins. These "hosts" contain molecular cavities for recognition of "guest" molecules,⁷ making them an excellent tools for the recognition and positioning of molecules. Based on these perspectives we have developed a new concept, that of "molecular printboards".

Resorcin[*n*]arenes-based adsorbates were shown to give well-packed, ordered monolayers⁷⁻¹⁰ capable of interacting with small guests such as tetrachloroethylene¹¹ and steroids,¹² and the self-assembly of molecular cages on gold surfaces.^{13,14}

Cyclodextrins (CDs) contain hydrophobic cavities lined by the glycosidic oxygen bonds. These are responsible for the ability of CDs to include hydrophobic molecules, and make them ideal hosts for molecular recognition. We have developed different routes for the immobilization of these molecular receptors on gold^{15,16} and silicon oxide¹⁷ surfaces. They form a densely packed, well ordered SAMs,¹⁵ the hexagonal packing of

which has been visualized by atomic force microscopy (AFM)^{18,19} (Fig. 1).

Molecular recognition at CD SAMs with anionic¹⁸ and neutral guest molecules¹⁶ was studied by means of surface plasmon resonance (SPR), electrochemistry and single molecule spectroscopy. In the last method, the rupture force of an individual host-guest complex was determined by pulling a guest-modified AFM tip off the host surface.^{19,20} The behavior at the surface and in solution was found to be very similar.

Furthermore, we have immobilized a wide range of molecules (calix[4]arenes, dendritic wedges, dendrimers and polymers) functionalized with multiple adamantyl and ferrocenyl units on CD SAMs on gold and silicon oxide surfaces.²¹⁻²⁷ Stable positioning and patterning of such molecules was achieved by means of multivalent supramolecular interactions between the hydrophobic moieties at the guest molecules and the CD cavities at the surface. Thus, these host surfaces serve as "molecular printboards" for the positioning of guest molecules.^{22,24} We have been able to

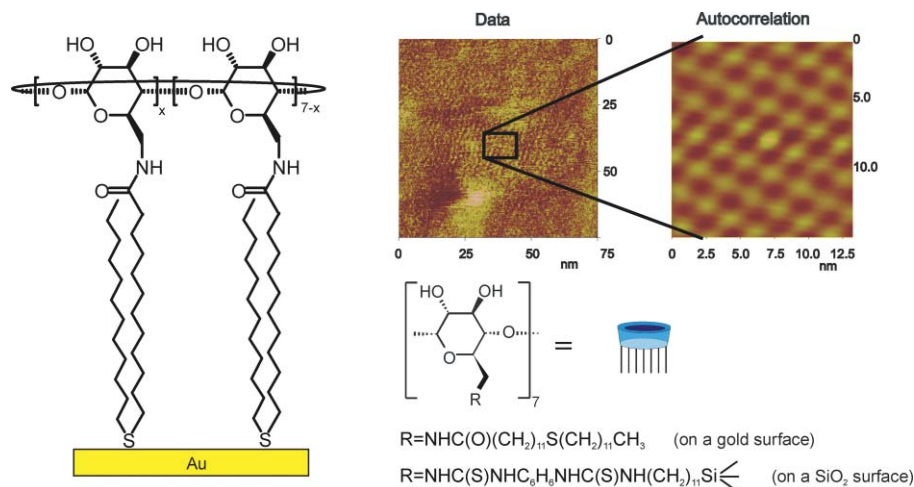


Fig. 1 Left: CD adsorbate on gold surface and (center) unfiltered friction mode AFM image of the CD-(OMe)₁₄ SAM. Top right: Autocorrelation filtered AFM height image of a CD-(OMe)₁₄ SAM. Both images were acquired by contact mode AFM in water.^{18,19} Bottom right: The two different CD host adsorbates on gold and on glass surfaces.

experimentally determine the number of interactions of these hydrophobically modified molecules towards the CD SAM, and therefore fine-tune the adsorption and desorption at surfaces depending on the number of interactions.^{24,26} Moreover, we have been able to electrochemically induce desorption at CD SAMs by using ferrocene-terminated dendrimers, revealing the possibility to intentionally adsorb and desorb molecules from the surface (Fig. 2).²⁵

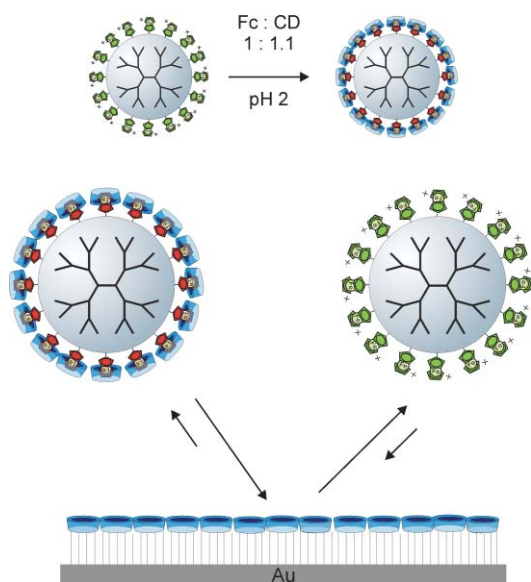


Fig. 2 Schematic representation of the absorption and electrochemical desorption of ferrocene-terminated poly(propylene imine) (PPI) dendrimers on CD SAMs.²⁵

Furthermore, patterns of guest-functionalized calix[4]arene molecules, dendritic wedges labeled with fluorescent groups, and dendrimers were created on these molecular printboards by using soft lithographic techniques such as microcontact printing (μ CP) and dip-pen nanolithography (DPN) (Fig. 3).^{22,23,28}

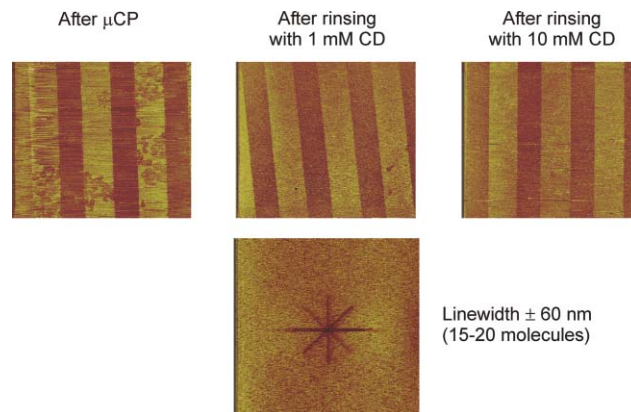


Fig. 3 Top: Contact-mode AFM friction images acquired in air of micrometer-size line patterns of adamantyl-terminated PPI dendrimer (generation 5, 64 adamantyl groups) (brighter areas) onto the CD SAM (image sizes $50 \times 50 \mu\text{m}$, friction forces [a.u.] increase from dark to bright contrast). Bottom: Contact-mode AFM friction images of an array of lines, $3 \mu\text{m}$ long with average widths of approximately $60 \pm 20 \text{ nm}$, of the adamantyl-terminated PPI dendrimer (generation 5, 64 adamantyl groups) after scanning the tip at a velocity of $\approx 4 \mu\text{m s}^{-1}$ across the CD SAM for 10 min for each line (image size $6 \times 6 \mu\text{m}$).²⁸

Dendrimers (in particular higher generations) can not only be immobilized on CD SAMs, but they also can efficiently encapsulate guests because the densely packed end-groups seclude the internal voids. Meijer and co-workers have introduced the term “molecular box” for a dendrimer that encapsulates one or more guest molecules.²⁹ On a surface these dendrimers provide the possibility to study and manipulate these molecules at a fixed position in space. The potential as a host of the immobilized dendrimers was investigated by encapsulating anionic dyes such as Bengal Rose and fluorescein. Confocal fluorescence microscopy showed that dendrimers can also function as molecular boxes when they are immobilized.³⁰ Moreover, more sophisticated strategies are possible: dyes were delivered to dendrimers by μ CP, and the

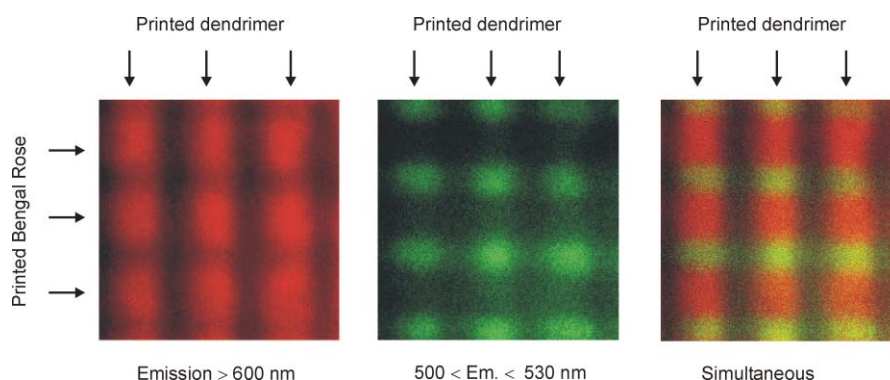


Fig. 4 Confocal fluorescence microscopy images ($50 \times 50 \mu\text{m}$) after microcontact printing of adamantyl-terminated PPI dendrimer (generation 5, 64 adamantyl groups) on a molecular printboard followed by cross-printing of Bengal Rose and subsequent filling with fluorescein. The substrate was simultaneously excited at 488 and 543 nm and images were recorded by measuring the emission above 600 nm (left), between 500 and 530 nm (center), and both simultaneously (right).³⁰

remaining empty areas could be filled selectively with a different dye from solution (Fig. 4).

Nanofabrication on molecular printboards

Electroless deposition: fabrication of metal patterns on the molecular printboard

Electroless deposition (ELD)³¹ is a routine and cost-effective fabrication technique for the selective deposition of metal on surfaces. To initiate ELD of metal onto surfaces, the only requirement is a surface bound catalyst. For this purpose, gold nanoparticles stabilized by fifth-generation (G5) PPI dendrimers were prepared, and subsequently transferred as catalysts for ELD onto the molecular printboard by supramolecular μCP .²⁸ AFM height images showed the specificity and selectivity of copper deposition on the areas patterned with dendrimer-stabilized gold nanoparticles on the molecular printboard (Fig. 5). The stability

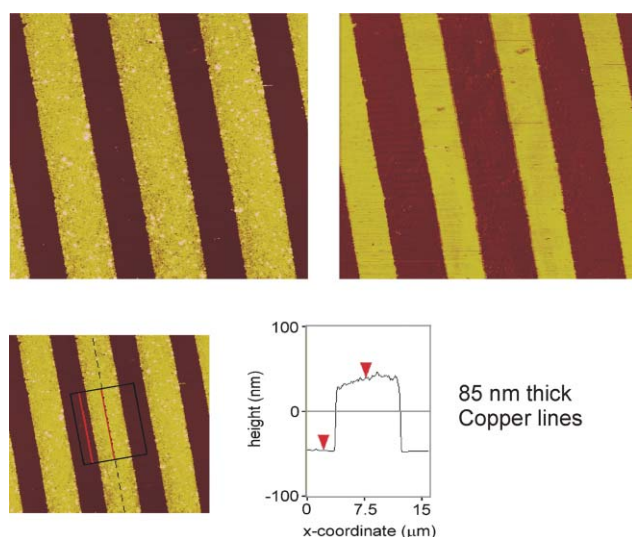


Fig. 5 Top: Contact-mode AFM height (top left, z range 200 nm) and friction (top right) images of copper structures obtained after electroless deposition (ELD) on the gold nanoparticle stabilized-adamantyl-terminated PPI dendrimers (generation 5) printed on the CD SAM. (Bottom) Height profile of ELD Cu deposition (images size $50 \times 50 \mu\text{m}$).²⁸

of these patterns is a consequence of the multivalent host-guest interactions of the dendrimer with the CD surface.

Supramolecular layer-by-layer assemblies on molecular printboards

In recent years, layer-by-layer (LBL)³² assembly has emerged as a promising method for fabricating structured and functional thin films on solid substrates. The LBL method allows the construction of a film on top of a substrate of almost any composition or topology by alternating exposure to solutions containing species with complementary affinities.³³⁻³⁵ Taking the molecular printboard as a platform, we have developed the stepwise construction of novel kind of self-assembled organic/inorganic multilayers based on multivalent supramolecular interactions between adamantyl-functionalized dendrimers (generation 5, 64 adamantyl groups) and cyclodextrin-modified nanoparticles, yielding supramolecular layer-by-layer assembly (Fig. 6).³⁶ The stepwise deposition was monitored by SPR, and further characterization of the multilayer films by means of UV/vis absorption spectroscopy showed a linear increase in absorption with the number of bilayers. Information on the thickness increase with the number of bilayers was obtained from ellipsometry and AFM. The multilayer thickness was found to increase linearly with the number of deposited layers, and an estimate of the multilayer thickness of 2 nm/bilayer was obtained.

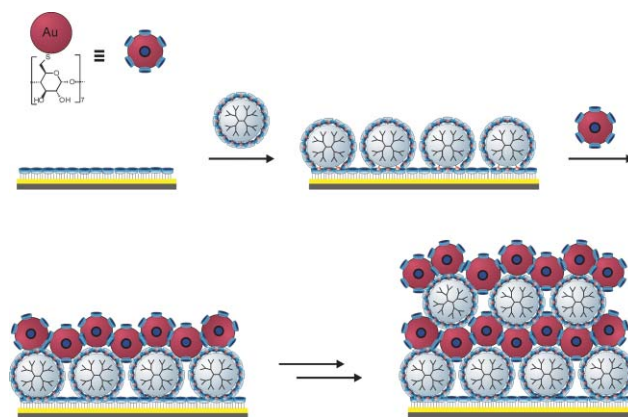


Fig. 6 Layer-by-layer (LBL) assembly scheme for the alternating adsorption of adamantyl-terminated dendrimer (G5) and CD-modified gold nanoparticles.³⁶

Conclusion and outlook

The molecular printboard is a versatile platform for the immobilization of molecules and nanoparticles on surfaces. Multivalent supramolecular interactions are the key to the controlled absorption of molecules and nanoparticles on surfaces. Molecules can be positioned onto the molecular printboard using supramolecular microcontact printing and supramolecular dip-pen nanolithography. At present we explore the integration of top-down and bottom-up methods to prepare functional nanostructured materials for application in bionanotechnology and nanoelectronics.

Acknowledgements

We are grateful to all colleagues and co-workers that have contributed to this work over the last years. We also acknowledge the financial support of STW (Simon Stevin Award "Nanolithography" to D. N. R.).

References

- General introduction to microfabrication: (a) W. Menz, J. Mohr and O. Paul, *Microsystem Technology*, Wiley-VCH, Weinheim, Germany, 2nd edn, 2001; (b) M. J. Madou, *Fundamentals of Microfabrication: The Science of Miniaturization*, CRC Press, Boca Raton, FL, 2nd edn, 2001.
- For a general review on nanofabrication, see: B. D. Gates, Q. Xu, M. Stewart, D. Ryan, C. G. Willson and G. M. Whitesides, *Chem. Rev.*, 2005, **105**, 1171–1196.
- G. M. Whitesides, *Small*, 2005, **1**, 172–179.
- Y. N. Xia and G. M. Whitesides, *Angew. Chem., Int. Ed.*, 1998, **37**, 551–575.
- B. D. Gates, Q. B. Xu, J. C. Love, D. B. Wolfe and G. M. Whitesides, *Annu. Rev. Mater. Res.*, 2004, **34**, 339–372.
- A. Ulman, *An Introduction to Ultrathin Organic Films: From Langmuir–Blodgett to Self-Assembly*, Academic Press, Boston, MA, 1991.
- K. D. Schierbaum, T. Weiss, E. U. Thoden van Velzen, J. F. J. Engbersen, D. N. Reinhoudt and W. Gopel, *Science*, 1994, **265**, 1413–1415.
- E. U. Thoden van Velzen, J. F. J. Engbersen, P. J. Delange, J. W. G. Mahy and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1995, **117**, 6853–6862.
- H. Schönherr, G. J. Vancso, B. H. Huisman, F. C. J. M. Van Veggel and D. N. Reinhoudt, *Langmuir*, 1997, **13**, 1567–1570.
- B. H. Huisman, E. U. Thoden van Velzen, F. C. J. M. Van Veggel, J. F. J. Engbersen and D. N. Reinhoudt, *Tetrahedron Lett.*, 1995, **36**, 3273–3276.
- B. H. Huisman, R. P. H. Kooyman, F. C. J. M. Van Veggel and D. N. Reinhoudt, *Adv. Mater.*, 1996, **8**, 561–564.
- A. Friggeri, F. C. J. M. Van Veggel and D. N. Reinhoudt, *Chem.–Eur. J.*, 1999, **5**, 3595–3602.
- B. H. Huisman, D. M. Rudkevich, F. C. J. M. Van Veggel and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1996, **118**, 3523–3524.
- E. Menozzi, R. Pinalli, E. A. Speets, B. J. Ravoo, E. Dalcanale and D. N. Reinhoudt, *Chem.–Eur. J.*, 2004, **10**, 2199–2206.
- M. W. J. Beulen, J. Bügler, B. Lammerink, F. A. J. Geurts, E. M. E. F. Biemond, K. G. C. Leerdam, F. C. J. M. Van Veggel, J. F. J. Engbersen and D. N. Reinhoudt, *Langmuir*, 1998, **14**, 6424–6429.
- M. R. De Jong, J. Huskens and D. N. Reinhoudt, *Chem.–Eur. J.*, 2001, **7**, 4164–4170.
- S. Onclin, J. Huskens, B. J. Ravoo and D. N. Reinhoudt, *Small*, 2005, **1**, 852–857.
- M. W. J. Beulen, J. Bügler, M. R. De Jong, B. Lammerink, J. Huskens, H. Schönherr, G. J. Vancso, B. A. Boukamp, H. Wieder, A. Offenhauser, W. Knoll, F. C. J. M. Van Veggel and D. N. Reinhoudt, *Chem.–Eur. J.*, 2000, **6**, 1176–1183.
- H. Schönherr, M. W. J. Beulen, J. Bügler, J. Huskens, F. C. J. M. Van Veggel, D. N. Reinhoudt and G. J. Vancso, *J. Am. Chem. Soc.*, 2000, **122**, 4963–4967.
- T. Auletta, M. R. De Jong, A. Mulder, F. C. J. M. Van Veggel, J. Huskens, D. N. Reinhoudt, S. Zou, S. Zapotoczny, H. Schönherr, G. J. Vancso and L. Kuipers, *J. Am. Chem. Soc.*, 2004, **126**, 1577–1584.
- A. Mulder, T. Auletta, A. Sartori, S. Del Ciotto, A. Casnati, R. Ungaro, J. Huskens and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 2004, **126**, 6627–6636.
- T. Auletta, B. Dordi, A. Mulder, A. Sartori, S. Onclin, C. M. Bruinink, M. Péter, C. A. Nijhuis, H. Beijleveld, H. Schönherr, G. J. Vancso, A. Casnati, R. Ungaro, B. J. Ravoo, J. Huskens and D. N. Reinhoudt, *Angew. Chem., Int. Ed.*, 2004, **43**, 369–373.
- A. Mulder, S. Onclin, M. Péter, J. P. Hoogenboom, H. Beijleveld, J. Ter Maat, M. F. García-Parajó, B. J. Ravoo, J. Huskens, N. F. Van Hulst and D. N. Reinhoudt, *Small*, 2005, **1**, 242–253.
- J. Huskens, M. A. Deij and D. N. Reinhoudt, *Angew. Chem., Int. Ed.*, 2002, **41**, 4467–4471.
- C. A. Nijhuis, J. Huskens and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 2004, **126**, 12266–12267.
- C. A. Nijhuis, F. Yu, W. Knoll, J. Huskens and D. N. Reinhoudt, *Langmuir*, 2005, **21**, 7866–7876.
- O. Crespo-Biel, M. Péter, C. M. Bruinink, B. J. Ravoo, D. N. Reinhoudt and J. Huskens, *Chem.–Eur. J.*, 2005, **11**, 2426–2432.
- C. M. Bruinink, C. A. Nijhuis, M. Péter, B. Dordi, O. Crespo-Biel, T. Auletta, A. Mulder, H. Schönherr, G. J. Vancso, J. Huskens and D. N. Reinhoudt, *Chem.–Eur. J.*, 2005, **11**, 3988–3996.
- J. F. G. A. Jansen, E. M. M. De Brabander-Van den Berg and E. W. Meijer, *Science*, 1994, **266**, 1226–1229.
- S. Onclin, A. Mulder, J. Huskens, B. J. Ravoo and D. N. Reinhoudt, *Langmuir*, 2004, **20**, 5460–5466.
- G. O. Mallory and J. B. Hadju, *Electroless Plating: Fundamentals and Applications*, American Electroplaters and Surface Finisher Society, Orlando, FL, 1990.
- G. Decher, *Science*, 1997, **277**, 1232–1237.
- P. T. Hammond, *Curr. Opin. Colloid Interface Sci.*, 1999, **4**, 430–442.
- G. Decher and J. B. Schlenoff, *Multilayer Thin Films*, Wiley, Weinheim, 2003.
- M. Schönhoff, *Curr. Opin. Colloid Interface Sci.*, 2003, **8**, 86–95.
- O. Crespo-Biel, B. Dordi, D. N. Reinhoudt and J. Huskens, *J. Am. Chem. Soc.*, 2005, **127**, 7594–7600.