Photochemical Single-Molecule Affinity Switch

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Molecular motors and anticipated future nanomachines rely on cyclic operation and external control. Mandatory for its reversible operation is the externally controlled and repetitive transition between at least two different molecular states, for example, by the conformational transition (switching) between two structural isoforms.[1] For the external control mechanism and transition stimulus, the interactions of molecules with light, electric, chemical, or mechanical potentials are known.[2−6] External activation via light is realized in natural sciences in various examples, such as photopolymerization, electronic excitation and energy transfer, ionic transport through membranes by light harvesting complexes, or energy up conversion in photosynthesis. Fundamental for all these processes is the ability to convert electromagnetic energy in conformational changes where specific and noncovalent bonds can be formed and released due to affinity changes. In order to investigate such phenomena in an artificial model system, we have synthesized a bistable supramolecular host−guest system where the supramolecular receptor cavity of a resorc[4]arene has been combined with two photodimerizable anthracene moieties whose structural conformation can externally switched by UV light and temperature. This photochemical macrocycle has been investigated in single-molecule force spectroscopy experiments by atomic force microscopy (AFM) for elucidating its functional properties to act as a photochemical single-molecule switch. In this report, we go beyond recent experiments where polymeric macromolecules have been investigated at the single-molecule level in order to build first mechanosensitive transducers by UV light[7] and redox reactions.[8]

Photochemical supramolecular host−guest systems on the basis of photoswitchable macrocycles have been investigated most recently in a number of publications.[9−11] On the basis of our research of photoswitchable resorc[4]arenes, we modified a difunctional resorc[4]arene with two anthracene units and proved its switching functionality in photochemical induction and heating cycles.[10,12] Moreover, we modified the *lower rim* of our resorc[4]-arene with four didecylsulfide linkers for an oriented surface immobilization on gold via molecular self-assembly (Figure 1).

This compound can repetitively be switched by photodimerization between the open and closed isoforms in ethanol by irradiation with UV light (360−370 nm) or vice versa by UV irradiation below 270 nm or by the transfer of thermal energy. In Figure 2, the UV absorption spectrum of this resorc[4]arene photoswitch is presented. Whereas in the open state the compound presents a cavity for the specific binding of ammonium ions,[13] the cavity is blocked in the closed configuration.

The affinity modulation of this optical switch was investigated by single-molecule force spectroscopy[14−18] similar to recent experiments where an affinity ranking of resorc[4]arene cavitand complexes with different (tetraorganyl)ammonium guests was reported.[19] Briefly, a resorc[4]arene self-assembled monolayer was immobilized
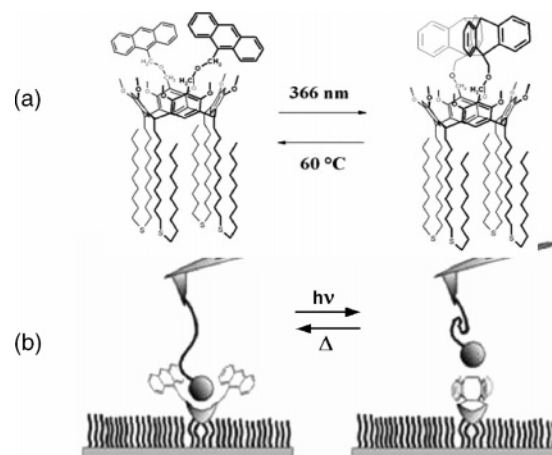
Figure 1. Resorc[4]arene photoswitch for self-assembly (a) and a pictogram visualizing the diluted self-assembled monolayer of this photoswitch for single-molecule affinity studies by AFM (b).
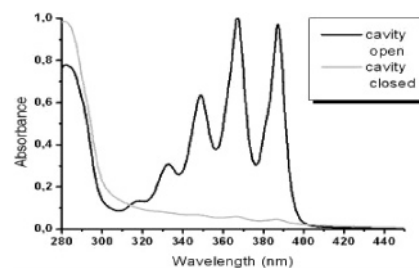

Figure 2. UV absorption spectrum of the resorc[4]arene photoswitch for the open and closed isomer. The peaks observed for the open isomer in the near UV are characteristic for the anthryl groups.

on a gold surface in a 1:40 dilution with dodecylsulfide. The guest molecule, an ammonium ion, was immobilized via an organic residue and a poly(ethyleneglycol) linker to an AFM tip. The switching from closed to open isomers was performed by heating the sample to 60 °C for 2 h. The cavity was closed by irradiation with a UV lamp at 368 ± 7 nm for 5 min.

Five series of force spectroscopy experiments were performed (Figure 3). The first series was measured on the open isomer after heating. The corresponding force histogram is given in Figure 3a and yields an overall binding probability of 9.1% and a dissociation force of 101 pN at a loading rate of 5260 pN s^{-1}. Then the sample was irradiated with UV light, and subsequently, a new force spectroscopy series was recorded. The corresponding force histogram is shown in Figure 3b. The binding probability was significantly lowered after irradiation to 0.9%. The very small number of events that still could be detected might be due to either incomplete closing or gradual reopening of the system. For the next series (Figure 3c), the sample was heated again for 2 h. The resulting force histogram closely resembles the first one (Figure 3a), yielding
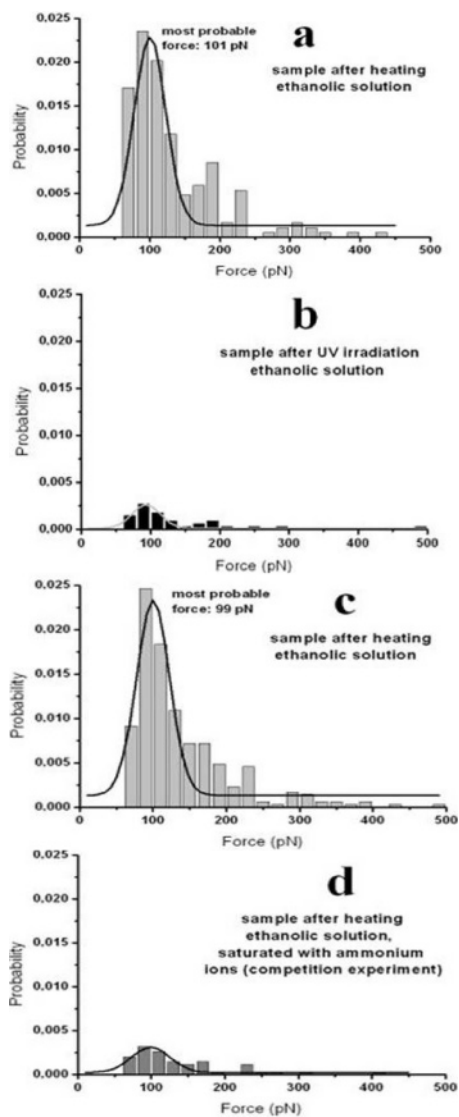
Figure 3. Single-molecule force spectroscopy experiments with the resorc-[4]arene photoswitch. (a) Experimental series after heating the sample to 60 °C for 2 h. (b) Series after irradiating the sample at 368 nm for 5 min. (c) Series after renewed heating the sample for 2 h. (d) Series of competition experiments, performed in ethanolic solution saturated with free ammonium. All experiments were performed with the same tip and sample at a retract velocity of 1000 nm s^{-1}.

a total binding probability of 9.6%, indicating that the reopening of the supramolecular host system was successful. In the next experimental series, a competition experiment in ethanolic solution saturated with ammonium chloride was performed (Figure 3d). The competition lowered the overall binding probability significantly (to 1.4%), though not to the extent which was observed after UV radiation. After washing the sample with ethanol, a last experimental series was performed, which again closely resembles the first one. The overall binding probability for the open system without competitor could be recovered (9.5%), indicating a reactivation of the surface.

These experiments prove that the resorc[4]arene can be reversibly switched between two different isomers which can be probed reproducibly and reversibly at the single-molecule level. Whereas one of the two isomers shows a high affinity to ammonium, the other exhibits almost none. From the results of the competition experiments, it can be concluded that the binding observed is selective toward ammonium.[13,19]

In addition to a recent investigation from our lab where we showed that single-molecule force spectroscopy (SMFS) is able to detect, quantify, and affinity-rank low-affinity noncovalent interactions in synthetic supramolecular complexes,[19] we have now applied this technique to an optomechanical switch. It could be shown in SMFS experiments that the reversible affinity switching of the receptor molecule by means of UV radiation (open → closed cavity) and heat (closed → open cavity) is possible and can be monitored by AFM. In the future, various novel applications are conceivable; for example, a self-assembled monolayer of a photoswitchable host molecule may serve as the prototype of a nanoscale rewritable memory which can be written or read by local UV irradiation. In addition, other host systems are currently under investigation such as switchable molecular capsules or artificial ion channels which might serve for a controlled transport and release of ions and neutral compounds.

Supporting Information Available: A general synthesis procedure and information about sample preparations for the single-molecule force spectroscopy and complete ref 11. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA067734H