

Single Conical Nanopores Displaying pH-Tunable Rectifying Characteristics. Manipulating Ionic Transport With Zwitterionic Polymer Brushes

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One of the remarkable aspects of the ever-growing field of nanotechnology relies on the creation of architectures with length scales and functional features comparable to biological machineries.¹ The progress in this field enabled the reproducible fabrication² of synthetic nanopores displaying properties that mimic their biological counterparts.³ Single conical nanopores are able to rectify the ion transport flowing through them, which is in close resemblance to voltage-gated biological ion channels.⁴ In this context, generating “fully synthetic” architectures with functionalities comparable to biological entities triggered the interest of the scientific community related to diverse research fields, including life sciences, chemistry, and applied biophysics.^{1,4} One of the central features that determine the rectifying characteristics of the conical nanopores is the nanoscale control over the surface properties of the pore walls.⁵ It has been demonstrated, both theoretically⁶ and experimentally,⁴ that the rectifying characteristics of the nanopores emerge due to a synergy of the entropic driving force caused by the channel asymmetry and the electrostatic effects due to the fixed charges on the pore wall. As a consequence, finding new avenues to manipulate the surface charges of conical nanopores is of paramount importance to further expand the potentialities of these nanosized systems.^{5,7,8} The development of functionalized conical nanopores with “smart” properties leading to the modulation of the fixed charges provides an exciting new approach to gain control over the ion transport through the nanopores. Controlling the permeation through membranes with pH-tunable moieties has attracted considerable attention during recent years.⁹ Seminal work of Martin and co-workers described the pH-switchable permselectivity of cylindrical cysteine-modified gold-coated nanotubules demonstrating the huge potential of zwitterionic moieties to tailor the surface charge properties of confined environments.¹⁰ On the contrary, in spite of its relevance, little is known about the behavior of rectifying conical nanopores bearing tailorable surface charges. In addition, to the best of our knowledge, the tailoring of the surface charge in single conical nanopores has been exclusively performed using monolayer assemblies. Within this framework, we have to note that polymer brushes provide a versatile toolbox to molecularly design interfaces with nanoscale control being applicable to a plethora of “smart” chemical functionalities.¹¹ For example, this chemical methodology would enable the facile construction of multiresponsive nanopores by simply using copolymer brushes incorporating different predefined functionalities.¹² More important, considering that the degree of rectification is highly dependent on the surface charge density,^{7c} polymer brushes provide a simple

means to sensitively increase the number of fixed charges on the nanopore walls. These particular features of polymer brushes merged with the transport properties of conical nanopores would open the door to completely new signal-responsive chemical nanodevices. In this work we demonstrate that the growth of zwitterionic polymer brushes provides a useful strategy to finely tune the rectifying characteristics of the nanopores and, consequently, to manipulate the mass or ion transport through them by simply varying the environmental pH.

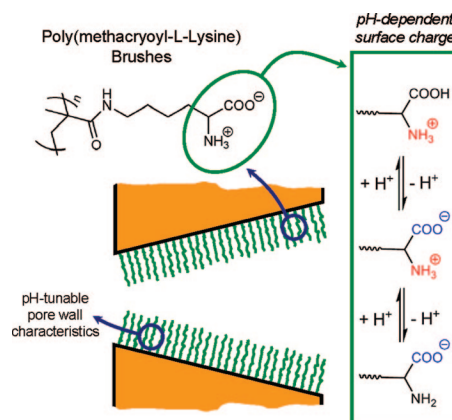


Figure 1. Schematic cartoon describing the polymer brush-modified conical nanochannel. The chemical structure of the polymer brush and the equilibrium associated to the pH-dependent behavior of the zwitterionic monomer units are also indicated.

Single conical nanopores, with a tip diameter (d) of ~ 20 nm and a base diameter (D) of $\sim 1.65 \mu\text{m}$, were fabricated by irradiation of polyimide (PI) films with single swift heavy ions as described by Apel et al.¹³ Then, the single nanopore-containing membranes were modified with 4,4'-azobis(4-cyanopentanoic acid) as the surface-initiated polymerization initiator (see Supporting Information (SI) for details).¹⁴ Afterward, the brush growth was accomplished by surface-initiated free radical polymerization of the zwitterionic monomer methacryloyl-L-lysine (Figure 1). After a preset polymerization time the membranes were thoroughly rinsed with Milli-Q water and mounted in the conductivity cell. Figure 2 depicts I - V curves of a single conical nanopore in PI modified with polyzwitterionic brushes using 1 M KCl (at different pH's) as the electrolyte solution in both half-cells. Considering the zwitterionic nature of the monomer units (Figure 1) we can infer that at strongly acidic pH's the monomer units covalently tethered to the pore wall will be bearing positively charged groups corresponding to $-\text{NH}_3^+$. As is well-known, the presence of rectification requires surface charges.⁵ In our case we observed that

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at pH 2 the I - V curve displayed a well-defined rectification behavior which would imply the permselective transport of anionic species through the positively charged nanopore (Figure 2). The degree of rectification (f_{rec}),^{7c} defined as the ratio between currents measured at voltages of the same amplitude but opposite polarities, was 22. At this point, it is worth mentioning that these results are similar to those previously reported in the literature using positively charged nanopores except for the higher degree of rectification, as compared with typical values for conical nanopores modified with monolayer assemblies, $f_{\text{rec}} \sim 5$.

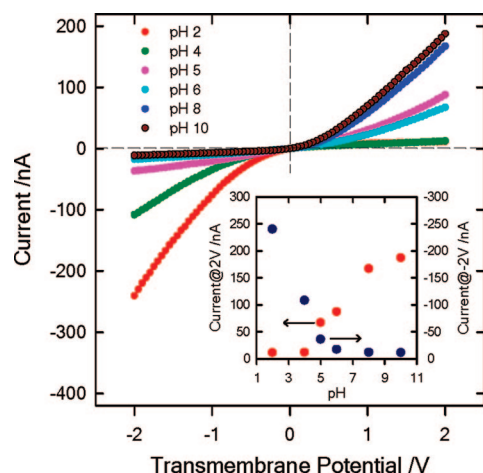


Figure 2. I - V curves corresponding to a single conical nanopore modified with poly(methacryloyl-L-lysine) brushes measured at different pH values (using 1 M KCl as electrolyte). The different pH's are displayed using colored symbols as indicated in the figure. The inset describes the changes in the rectified currents upon variation in the environmental pH. The red and blue dots refer to the rectified currents measured at 2 and -2 V, respectively.

The next goal was to achieve a fine-tuning of the surface charges to manipulate the ionic transport through the pore. As described in Figure 1, the equilibrium of the zwitterionic units involves a variety of charged states that are thermodynamically controlled by the pH value. So, we modified the acidic pH from 2 to 4, where the population of charged "bipolar" monomer units grew at the expense of the $-\text{NH}_3^+$ species resulting in a "less positive" surface charge. The I - V curve indicated that at pH 4 the well-defined rectification behavior was still observed, but in this case the rectified current had decreased. This variation in pH led to a significant decrease in f_{rec} from 22 to 9. This fact clearly indicates that the zwitterionic brush enables the tuning of the rectified current under the same permselective conditions. Then, increasing the pH to 5 resulted in a significant loss of the rectification behavior displayed by the pore. At pH 5 we are close to the isoelectric point of the zwitterionic brush (pI ~ 4.7) where the net charges are zero (see SI for details). The significant decrease of net surface charges explains the poor rectifying behavior displayed by the pore. However, at pH 5 we are slightly above pI and the presence of some negative net charges gives rise to the rectifying characteristics depicted in Figure 2 (pink trace). Increasing the pH above 5 promoted further displacement of the zwitterionic equilibrium toward the formation of negatively charged species (COO^-), thus reversing the permselectivity and rectification characteristics observed at acidic pH's. Changing the pH from 6 to 10 displayed a sensitive variation in the rectified

currents measured at $+2$ V from $+87$ to $+187$ nA, while the currents sensed at -2 V remained almost the same. In terms of f_{rec} the pH variation promoted a change from 5 to 17 in the rectification efficiency. This observation further indicates that, even in reversed permselective conditions, variations in pH can lead to the fine-tuning of the rectification characteristics.

In summary, we showed for the first time the integration of polymer brushes into conical single nanochannels to obtain highly functional chemical nanodevices. Our experimental evidence describing the use of zwitterionic brushes, and exploiting the pH-dependent chemical equilibrium of their monomer units, demonstrates that fine-tuning of the ionic transport by presetting the environmental pH is achievable and enables a higher degree of control over the ion transport properties of the system. We envision that these results will pave the way to new "smart" nanodevices based on the interplay between the chemical richness of polymer brushes and the remarkable physical characteristics of conical nanopores.

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Supporting Information Available: Detailed experimental procedures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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