

Molecular Modeling of Responsive Polymer Films

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Introduction

Responsive materials are those that have the ability to change their properties triggered by a change in the environment. Here we concentrate our attention on responsive surfaces. Namely, we consider surfaces with polymer coatings whose properties can be tuned and reversibly changed as a response to an environmental cue or an external applied field.^{1,2} For example, surfaces coated with a layer of polyacid can be negatively charged or neutral depending on the pH and/or ionic strength of the solution in contact with the surface.^{3,4} In general, the polymer backbones are hydrophobic and then the neutral coating becomes hydrophobic, changing the overall interactions of the surface with the solution.⁵

These general features of polymer coatings have been used extensively in the design of responsive materials.^{1,5–8} However, the discussion is in general framed in terms of the overall properties of the surface. Here we describe the current state of the art in molecular based modeling of responsive polymer films. In particular we emphasize the ability of the modeling approaches to describe the coupling between environmental stimuli and changes in the nanostructure of the layer. In other words, where changes in the solution properties or the application of an external field result in the controlled variation of the properties in regions of the surface at the nanoscale.

Nanoresponsive environments are very important in the design of a large variety of materials that include nanoactuators in which polyelectrolyte brush covered cantilever bending is driven by changes in pH,⁹ switchable cell culture surfaces, where changes in the structure of polymer layers induced by temperature changes are used to attach and release cells from surfaces,¹⁰ drug delivery systems where pH activates drug

release.¹¹ In other cases, some polyelectrolyte multilayer films develop nanopores upon changes in solution pH.^{8,12} A recent report disclosed the formation of phase-segregated spotted lipid or polymer micelles as a response to the presence of divalent metal ions in solution.¹³ In that case, ion binding to anionic amphiphiles causes segregation from neutral ones, an interesting example of surface reconstruction by coupled chemical equilibria (ion binding) and physical interactions. These examples show the broad range of applications for responsive systems. It is important to emphasize that chemical engineers with their strong background on thermodynamics and increasingly molecular modeling, are ideally suited to make major contributions to the rational design and understanding of responsive polymer films, with potential and proven applications ranging from ultrasensitive biosensors, drug delivery systems and switchable microfluidic devices to exquisitely sensitive separations.

The control of local environments of nanometer dimensions is in general a very challenging fundamental problem as it encompasses the understanding of how macroscopic changes, i.e., those in the solution, can be used to control local changes in regions with domains of nanometric length. Namely, the question is how bulk changes can lead to controlled inhomogeneities at the nanoscale? It is interesting to note that biological cells are multicomponent systems distributed in highly inhomogeneous environments where the relevant length scales are nanometers. The molecular organization within cells, or organelles in subcellular compartments, leads to the highly efficient ability of the cells to function. Consider, for example, lysosomes. These systems have a pH that is lower than the cytoplasm of the cell by around two units. This is needed in order to have the enzymes inside the lysosomes active.¹⁴ The question that arises is can we learn from biology how to design multicomponent systems that optimize their molecular organization and respond to environmental cues to provide function? In other words, how can we combine chemical reac-

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tivity and physical interactions to optimize the molecular organization and trigger function? The implication of this fundamental understanding to the rational design of responsive and biomimetic materials for the many possible applications mentioned previously is enormous.

In this Perspective, we will describe recent work on the molecular modeling of the coupling between chemical equilibrium and physical interactions in three systems. These systems incorporate different aspects of acid-base and redox chemical equilibrium coupled with hydrophobic polymers. The basic competition presented in these systems is the tendency of the backbone to collapse in order to avoid contact with the solvent and the need of the charged redox and/or acid groups to be surrounded by water. We will describe in detail how these systems self-assemble depending on the type of hydrophobic backbone and polymer surface coverage for different solution conditions and how they respond to changes in pH and ionic strength.

There are a variety of theoretical approaches to treat, at the molecular level, responsive polymer layers. The most detailed descriptions can be made with atomistic and coarse-grained Monte-Carlo (MC), and molecular dynamic (MD) simulations. However, the complexity of responsive polymer films makes the use of atomistic simulations prohibitively expensive. For example, the role of pH even for single small proteins is still not a resolved problem.¹⁵ However, recent work on lattice MC shows promise for treating charge regulation, i.e., pH, effects.¹⁶ Coarse-grained MC have been applied mostly on thermal responsive polymers,¹⁷ and MD have been recently used to predict the behavior of polyelectrolytes in poor solvents without charge regulation.¹⁸ The approximate molecular based approaches that have been used on responsive polymer layers include self-consistence field,^{4,19} density functional,²⁰ and molecular theories.^{21–23} The main difference between them is in the way that they treat molecular details. In this perspective, we concentrate on molecular theories. Their advantage is that they provide a systematic theoretical framework in which molecular information; interactions and chemical equilibrium can be incorporated. Thus, systematic calculations as a function of experimental accessible variables can be done obtaining detailed structural and thermodynamic information. However, their main limitations are: (1) they are based on approximate free energies in which not all the correlations are incorporated, and (2) the intermolecular interactions and the molecular models are treated approximately. Thus, at all stages of the application of theoretical methodologies comparison with detailed simulations and experimental observations, whenever they are available, are needed to check the validity of the approximations used. Once the quality of the approximations is asserted systematic studies can be done.

The molecular theory that we describe was originally developed to treat surfactant self-assembly²⁴ and generalized to treat a large variety of polymeric and surfactant systems.²¹ The approach is based on explicitly including the chemical nature of all the molecular species. The theory includes the size, shape, conformations, charge and charge distribution of each of the molecular species. For example, for the polymer chains one needs to generate all the possible conformations. This is possible for short chains (surfactants and lipids), while for long chains one generates a very large representative sample of the conformations. The theory determines what the proba-

bility is of each of those conformations depending on the conditions. Namely, the probability of each chain conformation is the one that minimizes the total free energy of the system for the given set of experimentally controlled variables such as temperature, ionic strength and bulk pH among others. It is important to emphasize that the probability also contains the degree of charge of the polymer and the oxidation state of the redox sites. Therefore, since these quantities depend on the position then the probability of the different polymer conformers results from the nontrivial coupling of the local interactions and chemical equilibrium and their relationship to the bulk solution.

Redox Polymer Modified Electrodes

The first system that we describe corresponds to a gold electrode surface with a self-assembled thiol monolayer of mercapto-propansulfonate (MPS). On the sulfonate surface there is a single layer of adsorbed redox polymer. The chains of the redox polyelectrolyte PAH-Os (see structure in Figure 1A) are composed of a polymer backbone (poly-allylamine) derivatized with covalently tethered osmium pyridine-bipyridine complexes (osmium sites). The redox polymer modified electrode is in contact with a saline solution of a given pH. The system is schematically shown in Figure 1A. These electrodes find applications in biosensors²⁵ and biofuel cells.²⁶

The theoretical treatment of this system requires the formulation of a free energy that includes the following terms: the translational entropy of mobile ions and water molecules, the conformational entropies of the polymer chains, the conformational entropies of thiol molecules, the polymer amino groups acid-base chemical free energy, the sulfonate from the MPS acid-base chemical free energy, the osmium redox free energy, the work required for electrons from the electrode to participate in the redox reaction, the van der Waals (vdW) polymer-polymer interactions, the electrostatic interactions, the van der Waals (vdW) polymer-surface interactions and the excluded volume intermolecular repulsions between all the molecular species. As explicitly shown in references 22,23,27,28 the different terms in the free energy are formulated as functionals of the different density distributions, the probability distribution function of the chain conformations, the position dependent fractions of acid (base) and oxidized (reduced) groups. These quantities are determined by functional minimization of the free energy. We now describe some of the results for this system with an emphasis on the relationship between the molecular organization of the film and the electrochemical behavior.

It has been shown that the electrode capacitance as a function of the electrode potential as predicted from the molecular theory is in very good agreement with the experimental observations.^{22,27,28} The capacitance-potential curves present a peak due to the oxidation/reduction of the osmium complexes in the redox polymer. Figure 1B shows the position and width of the redox peak as a function of solution ionic strength. In all the range of results shown there is very good agreement between the experimental observations and the theoretical predictions. The same level of agreement is found as a function of the bulk pH.²⁷

The good predictive power of the theory over a wide range of experimental variables, without the use of adjustable pa-

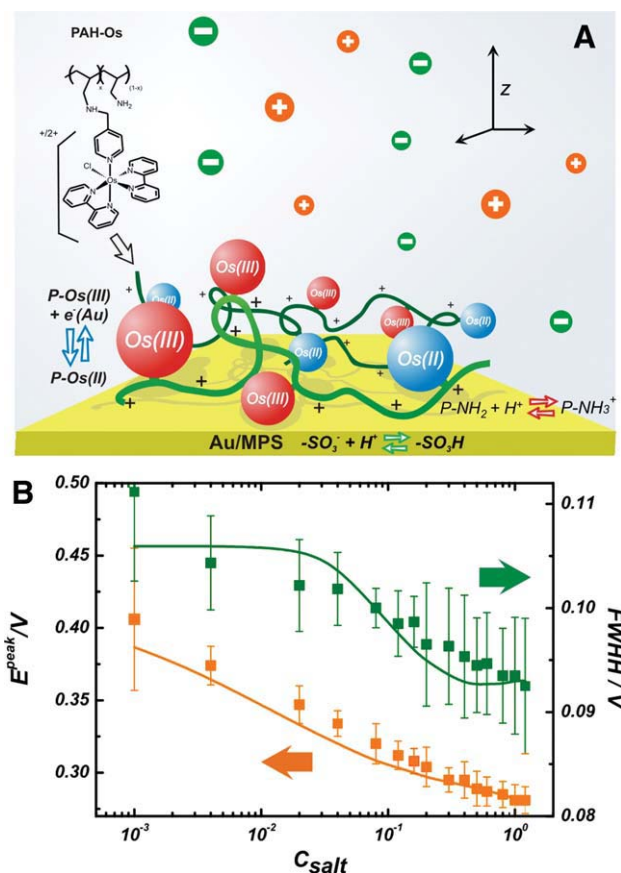


Figure 1. (A) Schematic representation of the Au/MPS/PAH-Os modified electrode: the redox polymer is composed of a poly(allylamine) backbone (green lines) and a tethered electroactive osmium pyridine-bipyridine complex, which can be either reduced (Os(II), blue spheres), or oxidized (Os(III), red spheres).

The oxidation fraction depends on the potential at the electrode and the local environment of the redox sites. The allylamine units in the polymer backbone can be either protonated (positively charged), or deprotonated (neutral). The redox polymer is adsorbed on a gold electrode modified by the thiol mercaptopropylsulfonate (MPS). The terminal sulfonate groups of MPS participate in an acid-base equilibria, and, therefore, can exist in a negatively charged state or in a protonated neutral state. The electrode is immersed in a solution containing solvent molecules (water), salt ions (Na^+ and NO_3^-), protons and hydroxyl ions. (B) Comparison between experimental (symbols) and theoretical (line) current-voltage peak potential (E^{peak} , left axis, orange), and peak width at half height ($FWHH$, right axis, green) as a function of salt concentration for a pH 3 solution (adapted from refs. 22,27,28)

rameters, provides with confidence that the approximations used in the derivation of the theory are appropriate. Moreover, it supports the idea that molecular modeling can become an integral part in the design of responsive chemical and electrochemical surfaces. Furthermore, there is an important fundamental component that provides with exquisite details for

what are the molecular sources and interactions that lead to the observed changes in the apparent redox potential of the film as a function of ionic strength and bulk pH.

The peak position moves toward lower values and the width of the capacitance-voltage curves decreases as the ionic strength increases. One can explain these findings in terms of simple arguments such as the presence of a Donnan potential difference between the polymer and the solution phases. At decreasing ionic strength, a positive Donnan potential arises from the large concentration of protonated amines and osmium sites within the film,^{29,30} and produces an increase in the free energy cost of converting osmium (II) to osmium (III), shifting the redox peak to higher potentials. However, while the Donnan model makes use of free adjustable parameters, the molecular theory predictions are from first principles. Moreover, the detailed molecular organization and the variation of the apparent redox potential with distance that is determined from the molecular theory shows that the picture is more complicated than that considered by the Donnan model. Detailed calculations show that the polymer film presents a highly inhomogeneous distribution of polymer backbone segments and redox sites.²² Interestingly, it is found that the oxidation state of the redox sites can change by more than a factor of two within a couple of nanometers. These changes are the result of the coupling between the electrochemical state of the sites, the molecular organization of the film and the intermolecular interactions.

The results presented in Figure 1 and in references.22,27,28 demonstrate the importance of understanding the molecular organization and local chemical state in order to design function. Namely, the apparent redox potential of the polymer modified electrode is an average over a large distribution of values, and, therefore, assuming the oxidation state to be constant would provide with the qualitative wrong picture. This will be further shown when we discuss Figure 3 the role of domain formation on the electrochemical response of redox polymer modified electrodes. Before we get to that system we will discuss the spontaneous formation of different morphologies in weak polyelectrolyte brushes.

Domain Formation in End-Grafted Hydrophobic Weak Polyacids

Consider next a system in which the polymer molecules are end-grafted to the surface, their backbone is hydrophobic and they contain acid (or basic) groups. This is usually called weak hydrophobic polyelectrolytes. These systems find applications in drug delivery³¹ and they present potential for the design of smart surfaces.^{5,32} The question that we address is what is the structure of this polymer layer and how that structure changes with the quality of solvent, the solution ionic strength and the bulk pH. Neutral polymers in poor solvents[†] are known to collapse into small compact globular forms in order to avoid as much as possible contact with the surrounding solvent.^{33–35} The gain in intramolecular attractions is

[†]Poor solvent refers to the case in which the polymer segments prefer to be in contact with polymer segments rather than solvent. Hereafter, we will refer to poor solvent also as low-temperature or strong hydrophobic interactions. In the molecular theory it corresponds to small values of χ_c/χ , where χ is the characteristic interaction energy normalized by the thermal energy kT and χ_c corresponds to value of χ in which the homogeneous uncharged polymer layer becomes unstable.

accompanied by a loss of conformational entropy. A grafted polymer layer in poor solvent shows self-assembly properties since macrophase separation is not possible due to the lack of translational degrees of freedom of the polymer molecules.²³ Thus, at low-surface coverage they form micelles, whose size and shape are characterized by the interplay between line tension and stretching free energy.³⁶ In other words, depending on surface coverage and temperature one finds hemi-spherical octopus micelles, stripes of long aggregates or homogeneous brush-like compact layers.^{36–39}

The stability of the different morphologies changes in the case that the monomers can have charge.^{18,23} This is specifically shown in Figures 2 for a system of end-grafted polyacids with a hydrophobic backbone (Figure 2A). The morphology phase diagram in the plane of strength of hydrophobic interactions and bulk pH is shown in Figure 2B. There are five different regions that represent the different morphologies. Before we discuss each one of them it is important to mention that the phase diagram that is obtained for the same system but without allowing local charge regulation provides the wrong qualitative results in terms of the morphologies that can be formed, and it misses much of the important physics of the problem.²³ Thus, both at the fundamental level and for the design of responsive surfaces, the explicit incorporation of the coupling between chemical equilibrium (acid-base in these systems), physical interactions and molecular organization is imperative for the proper description of these complex systems.

The morphologies that self-assemble are shown as isodensity maps in Figure 2B. At relatively weak hydrophobic interactions (corresponding to high values of χ_c/χ in Figure 2B) the polymers form a homogeneous brush. As the hydrophobicity of the polymer increases at low pH there are three different morphologies that correspond, from weak to strong hydrophobic interactions, to layers with holes, stripes of elongated aggregates and quasi-spherical micelles. The thermodynamic description of the different morphologies is not the same as that of surfactant self-assembly since the polymer molecules have one of their ends chemically grafted to the surface. Therefore, they have no translational degrees of freedom and then thermodynamic equilibrium is not given by equality of polymer chemical potentials.²³ Actually, the chemical potential is not a thermodynamic relevant variable, and the understanding of what stabilizes each structure is given by the competition of the different interactions and the charge state of the polymers as described in detail next.

At the lowest pH shown the degree of charge of the polymers is very low and the system can be understood in the same terms as uncharged end-grafted polymers in poor solvent. As the quality of the solvent decreases (lower χ_c/χ in Figure 2) the homogeneous layer becomes unstable due to the need of the polymer to maximize polymer-polymer contacts. The sequence of aggregates shown clearly demonstrates the tendency of the system to optimize polymer-polymer contact while maximizing the conformational entropy. The local volume fraction of the aggregates is larger for the more compact morphologies, which also corresponds to a decrease of conformational entropy. Thus, the micelles form for most hydrophobic polymers. The interplay between quality of the solvent and chain stretching is not enough to explain the morphological changes that occur as the pH increases. An example is that the predicted temperature for the transition from stripes to

micelles is constant in the range $3 \leq pH \leq 5$. The bulk pK_a of the acidic segments is 5, thus, assuming homogeneous charging according to the bulk formulation, i.e., $f = 1/(1+[H^+]/K_a)$, the fraction of charged polymer groups in this range would be $0.01 \leq f \leq 0.5$. One would expect the solubility of the polymers at $f = 0.5$ to be much larger than that at $f = 0.01$.[‡]

The calculations show that the degree of charge of the polymers in the range $3 \leq pH \leq 5$ does not change much (see Figure 3B of ref. 23). Therefore, in this range of pH the attractions between the polymer segments dominate. Namely, as the pH increases the chemical component (acid-base) of the free energy will move the system toward an increased polymer charge. However, the quality of the solvent remains poor and thus the polymers would like to have a large-volume fraction within the aggregates. If the system were charged the electrostatic repulsions would destabilize the aggregates. The fact that the system continues to have micelles with high-local volume fraction and a low degree of charge implies that in this regime the optimal *overall* state of the system is such in which the hydrophobic attractions gain and the reduction of electrostatic repulsions is more convenient than the loss of chemical free energy. This charge regulation is the origin for the lack of bulk pH dependence on the stripes to micelle transition, i.e., the horizontal line in Figure 2B between micelles and stripes. As the pH increases above 5 there is a new morphology that, to the best of our knowledge, was first described in ref. 23. The green regime in Figure 2B corresponds to the coexistence of micelles with stretched chains and it originates from the best way that the system has to optimize charge regulation, hydrophobic interactions and molecular organization.

The microphase separation of the end-grafted polymers is the result of the lack of translational degrees of freedom of the chains. Otherwise, the system would macrophase separate. The morphology of micelles coexisting with nonaggregated polymers is very interesting because the properties of the chain molecules in the micelles and those that are nonaggregated are completely different. The chains in the micelles are collapsed, while those nonaggregated are stretched. More importantly, the degree of charge of the nonaggregated polymers is much higher than those in the micelles. Thus, the competition between the hydrophobic repulsions, the chain stretching and the chemical free energy is balanced in this regime by separating the system into two types of molecules: (1) the aggregates, which look like those in the low pH regime, and (2) the nonaggregated that resemble those in the homogeneous brush. Note that further increase of the pH results in charged polymers forming a homogeneous brush, since the electrostatic gain in solubility overcomes the hydrophobicity of the backbone.

The division of different domains coexisting is interesting because it provides for nanometer-size regions where the local pH can be controlled and whose value can be different from the bulk solution by one or two units, depending on the bulk solution ionic strength. These domains can be used as microreactors or to drive the motion of nanoparticles.³⁷ Furthermore, it demonstrates the nontrivial and important interplay between chemical equilibrium and physical interactions which is highly nonadditive.

[‡]It is important to mention that in the morphological phase diagram predicted *without* including the coupling of charge regulation and physical interactions, i.e., assuming the f is determined from its bulk value, the boundaries between the different domains are qualitatively different than those presented in Figure 2 and the green region does not exist.²³

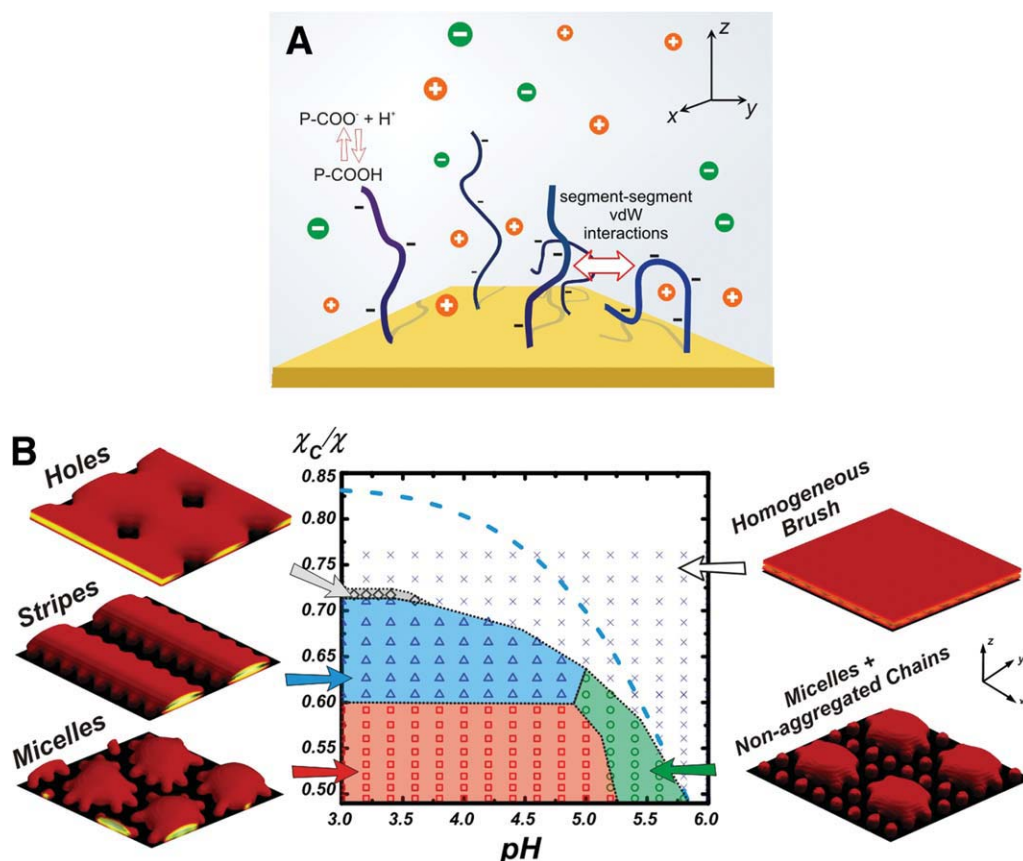


Figure 2. (A) Schematic representation of end-grafted weak polyacid layer with hydrophobic interactions. Each segment bears a carboxylate group that can be either protonated (neutral), or deprotonated (negative). Segment-segment attractive nonelectrostatic interactions are stronger than solvent-segment interactions, and, therefore, the polymer backbone is hydrophobic (i.e., it is in poor solvent conditions). The system is immersed in a bulk solution containing water molecules, salt ions, protons and hydroxyl ions. (B) Morphology diagram for the system in A.

The diagram shows the plane defined by the bulk pH and the parameter χ_c/χ . This parameter is a measure of the hydrophobicity of the polymer backbone, lower χ_c/χ corresponds to more hydrophobic polymer (poorer solvent). The symbols in the diagram represent the different morphologies adopted by the polymers: squares (micelles), triangles (stripes), rhomboids (holes), circles (micelles and nonaggregated chains), crosses (homogeneous brush). Each point in the diagram is obtained by solving the theory for a given set of bulk (experimentally controlled) conditions (see ref. 23). The blue dashed line indicates the onset of stability of the homogeneous brush (calculated with a 1-D (1-dimensional) molecular theory, see ref. 40). Typical examples of the polymer layer morphologies are shown as isodensity surfaces for $\langle \phi_p(r) \rangle = 0.15$, where $\langle \phi_p(r) \rangle$ is the average polymer volume fraction at r . Other calculation parameters were N_p/A (grafting density) = 0.111 chains/nm², n (segments per chain) = 50, $C_{\text{salt}} = 0.1$ M and pKa = 5.0, adapted from ref. 23.

End-Grafted Redox Polymers: Domain Formation and Electrochemistry

The two systems reviewed previously raised the following questions: (1) can one control the morphology of end-grafted polymers with redox side chains, and (2) how the morphology transformations would be reflected in the electrochemical behavior of the modified electrode. Namely, what are the properties of end-grafted polymers with hydrophobic backbones, where a fraction of the segments bear redox sites? In Figure 3A, we depict an example of such systems. The oxidized state of the electroactive segments corresponds to a charge of +1, and the reduced state is neutral. It is important to emphasize that for these redox polymers the experimental controlled variable that modifies the state of charge of the

polymer is the potential applied on the electrode. Furthermore, there is an important difference with the system described in Figure 2A, since in the electroactive brush the charge regulation is given by the effect of the local environment on the free energy cost required to inject/extract electrons to/from the redox sites. As explained in ref. 22 the theory explicitly includes the chemical potential of the electrons, that depends on the applied electrode potential. Upon changes in the applied electrode potential the polymers can go from uncharged (reduced) to charged (oxidized), and as such we expect that for poor solvents the system may form domains whose morphologies can change with the applied potential. Furthermore, if this is indeed the case, is there a signature of these changes that is manifested in the capacitance-voltage curves?

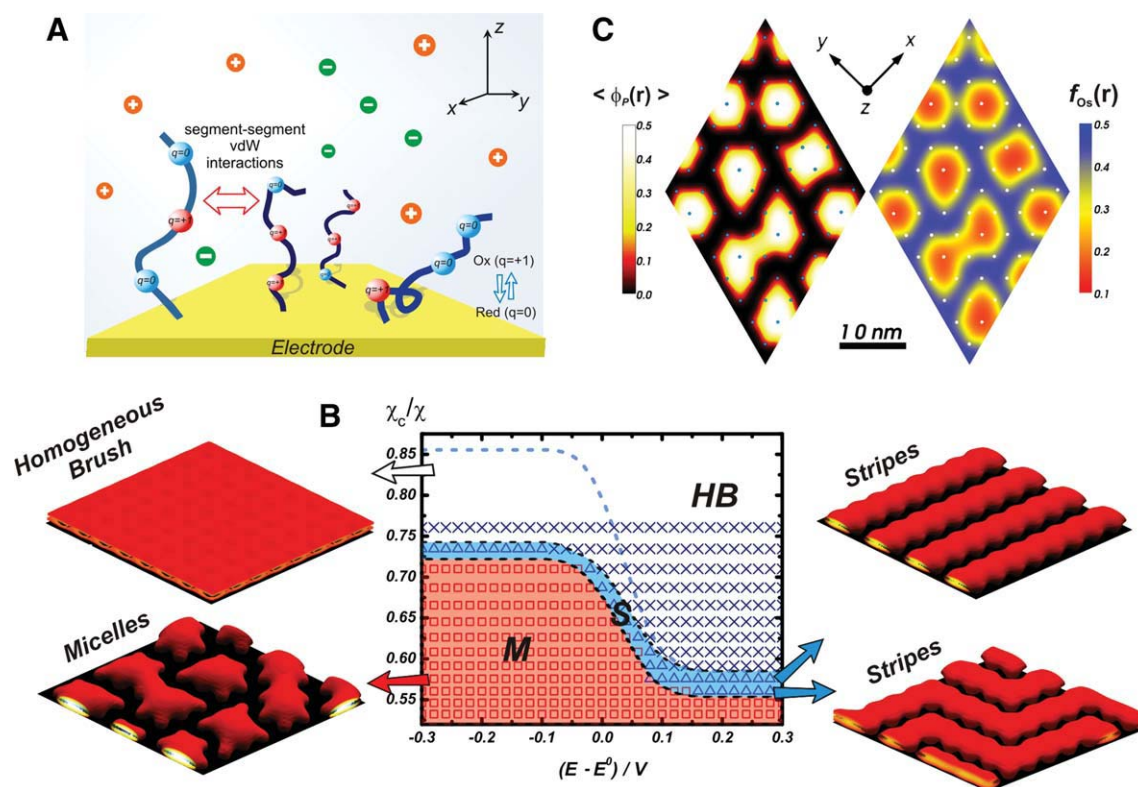


Figure 3. (A) Schematic representation of the model end-grafted redox-active hydrophobic polymer layer. Each polymer chain contains both redox-active (spheres) and neutral electroinactive segments (blue lines). The redox-active segments can exist either in an oxidized form bearing one positive charge (red spheres), or in a reduced neutral state (blue spheres), depending on the potential at the electrode and the local environment. The chains are tethered to an uncharged short thiol layer that covers the electrode. The modified electrode is immersed in a bulk solution of water molecules, salt ions, protons and hydroxyl ions. (B) Morphology diagram for a ratio of redox-active to total segments of 10:50.

The symbols in the diagram represent the different morphologies adopted by the polymer layer: squares (micelles), triangles (stripes) and crosses (homogeneous brush). The blue dashed line is the stability line for a homogeneous brush. Typical examples of the polymer morphologies are shown as isodensity surfaces for $\langle \phi_p(r) \rangle = 0.15$, where $\langle \phi_p(r) \rangle$ is the average polymer volume fraction at r (two different examples of the stripes morphology are shown). (C) Color maps of the polymer volume fraction, $\langle \phi_p(r) \rangle$, (left) and the fraction of oxidized redox-active segments, $f_{Os}(r)$, (right) along a plane parallel to the surface ($z = 2$ nm) in the M regime ($\chi_c/\chi = 0.61$ and $E = E^0$). Other calculation parameters were N_p/A (grafting density) = 0.082 chains/ nm^2 , $C_{\text{salt}} = 0.1$ M and $\text{pH} = 7.0$.

Figure 3B shows the morphology phase diagram for polymer molecules with 10 of their 50 segments having redox groups. The plane shown is hydrophobic interactions-applied potential. There are three different morphologies for this case. They are micelles, stripes and homogeneous brush. At fixed hydrophobicity, for $\chi_c/\chi > 0.58$, increasing the applied potential leads to the oxidation of the redox sites destabilizing the micelles, and if enough charges are present, stripes form that at high-enough potentials convert to homogeneous brush structures. For stronger hydrophobic interactions, the total charge on the polymers is not enough to compete with aggregation and the micelles are the only stable morphology. As it was the case discussed with the weak polyelectrolytes, the coupling between charge regulation and the physical interactions determines the morphology and stability of the domains. Interestingly, charge regulation by redox equilibrium is not identical to charge regulation by acid-base equilibrium. However, the general features are similar. Namely, that the state of

charge depends strongly on the optimization of the chemical equilibrium, the physical interactions and the morphology of the aggregates. The redox polymers, however, can lead to interesting electrochemical behavior that can be observed experimentally. The predicted shapes of the voltammograms depend on the strength of hydrophobic interactions, reflecting that molecular organization within the film determines the electrochemical response.

In weak polyelectrolytes the local degree of charge can vary by a large amount within a few nanometers due to the formation of domains. The degree of oxidation in the aggregates of redox polymers is expected to be highly inhomogeneous and to reflect the shapes of the domains. This is shown in Figure 3C where a density map of the polymers at distance 2 nm from the surface is shown. The density maps clearly show the presence of the surface micelles. Also shown is the fraction of oxidized redox groups on the same plane. The fraction of oxidized groups is a very sharply varying function of the

local density and its distribution reflects the local environment of the polymer. We see that in the inner core of the micelles, where the volume fraction of polymer is maximal, the fraction of oxidized groups is 0.1 even though the applied potential is that that would correspond to 0.5. Note that in the boundary of the micelles the fraction is 0.3. The reason for the fraction of oxidized groups to decrease with the volume fraction of the polymer is that the system prefers to pay in chemical (redox) free energy by shifting the equilibrium to the reduced state in order to decrease the local charge, and as a result the repulsive electrostatic interactions. Interestingly, the results presented in Figure 3 demonstrates that one can design surfaces with local variations in the apparent redox potential with large gradients in all three directions and that can be controlled by varying bulk experimental variables. It is interesting to note that the transition from micelles to stripes of redox polymers have potential application on switchable electron transfer devices. Namely, the stripes present continuous environments for the lateral movements of electrons through the polymers while the micelles do not.

Conclusions

In this perspective, we have shown three different cases of responsive polymers at surfaces where the properties of the surface can be varied in response to cues from the bulk solution or in the presence of an external field. The most important conclusion in all three cases is that the chemical reaction equilibrium, physical interactions and molecular organization are strongly coupled, and it is imperative to consider the global and local changes that occur to the surface structure and properties due to this coupling. In particular acid-base and redox equilibrium are very different in polymer-modified surfaces than in the corresponding bulk solutions. Moreover, the definition of “apparent redox potentials” and “apparent pK_a ” results from the averaging over highly inhomogeneous values, and, therefore, they do not necessarily represent the state of the layer and the local values and their variation are very important for the design of functional surfaces. The very large variation on chemical equilibrium results from the optimization of all the interactions. The picture that emerges is that trying to deduce what the final state of the system is by looking at the individual optimization of each contribution leads to qualitative incorrect assumptions and only the minimization of the complete free energy leads to the proper behavior in these complex systems.

In the cases where domain formation is possible in grafted weak polyacid layers charge regulation may lead to regimes of coexistence between aggregates with relatively low fraction of charged polymer segments surrounded by highly stretched chains that have a relatively high fraction of charged groups. Therefore, one can control the state of charge, local electrostatic potential and local pH in all three dimensions with important gradients on length scales of nanometers. For hydrophobic redox polymers we show how the application of an electrode potential can lead to changes in the structure and type of morphological aggregates that can form on the surface. Again, these structures result from the optimization of chemical redox equilibrium, conformational entropy, electrostatic and hydrophobic interactions. Furthermore, changes in domains structure can manifest themselves in the capacitance-

potential curves and then provide a link between macroscopic measurements and the formation of nanoscopic domains. It is clear that chemical engineers are in a unique position to use these switchable surfaces in the molecular design of sensors, biosensors, separation devices, microfluidic devices with on-off environmental switches and drug delivery systems among many others.

Finally, we want to stress that the application of molecular theories, where the coupling between chemical equilibrium, physical interactions and molecular organization are explicitly included provide with quantitative predictions of the layers properties, as compared with experimental observations, and enable the fundamental understanding of the observed behavior. Moreover, the theory provides with a detailed microscopic picture and should be used as an integral part in the design of functional and responsive surfaces. It is important to emphasize that the molecular approaches are not exact, and, therefore, there is a need to continue their development and the incorporation of improved approximations to further broaden their applicability.

Acknowledgments

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