consistency, benzaldehyde was used exclusively as the aldehyde component in these reactions.
[24] *Anti* refers to the relative stereochemistry of the hydroxy and side-chain groups, for example, product **6a** as drawn.
[25] C. W. Lee, R. H. Grubbs, *Org. Lett.* **2000**, *2*, 2145.
[26] Wuts et al. were first to prepare the analogous THP-protected (THP = tetrahydropyran) hydroxymethyl products by means of allylboration; see ref. [17b].
[27] This substrate isomerizes to the corresponding silyl enol ether under the reaction conditions, resulting in the varying yields of **6b**: C. W. Lee, R. H. Grubbs, unpublished results.
[28] D. J. O'Leary, H. E. Blackwell, R. A. Washenfelder, K. Miura, R. H. Grubbs, *Tetrahedron Lett.* **1999**, *40*, 1091.
[29] Alcohol **6e** was synthesized in only 36% yield with a 2:1 *anti*:*syn* ratio when allyl bromide was used as the cross partner.
[30] A. K. Chatterjee, R. H. Grubbs, unpublished results.
[31] This is in stark contrast to previous studies in which hindered olefins could be used in nearly equal stoichiometric amounts with terminal olefins as a result of the slow dimerization of the hindered substrates; see ref. [11].

## Electrodeposition of Redox Polymers and Co-Electrodeposition of Enzymes by Coordinative Crosslinking**

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The electrodeposition of metals and electron- or hole-conducting polymers proceeds through forming metallic or covalent bonds, respectively. We show here that films of hydrated redox polymers can also be electrodeposited. Electron conduction in redox polymers derives of the mobility of their segments. When the polymers are hydrated, their mobile segments randomly collide. Upon colliding, reduced mobile segments transfer electrons to oxidized ones.[1–9] The electrodeposition of redox polymers results of the formation of coordinative bonds that crosslink the chains.

The electrodeposited polymers were water soluble and comprised backbone-bound ligands and $Os^{2+}/Os^{3+}$ complexes with exchangeable $Cl^-$ ions in their inner coordination sphere. When the polymers were adsorbed on electrodes and were electroreduced, they were crosslinked by ligand exchange: about 5–10% of the labile $Cl^-$ ions of the Os complexes of one polymer chain were exchanged by the more strongly coordinating pyridine or imidazole functions of neighboring chains.

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It is well known that transition metal ions exchange ligands when electroreduced and/or electrooxidized.[10–14] It is also known that upon illumination the redox polymer formed by coordinating $[Ru(bpy)_2Cl]^+/[Ru(bpy)_2Cl]^{2+}$ to poly(4-vinylpyridine) exchanges its inner-sphere chloride with water, perchlorate or acetonitrile.[15] Here we show that when the initially reversibly adsorbed water-soluble redox polymers are electrochemically cycled, they are irreversibly crosslinked and are thereby irreversibly electrodeposited. The resulting films conduct electrons when they are hydrated, and their redox segments are mobile enough to collide, even though they are tethered to the crosslinked polymer. The deposition is rapid (200 s) and takes place at 25 °C in aqueous solutions at neutral pH. As the crosslinking caused by ligand exchange proceeds under mild conditions, dissolved enzymes with amine or heterocyclic nitrogen functions coordinating transition metals are conveniently co-electrodeposited. Substrates of the enzymes are electrocatalytically oxidized/reduced on the resulting "wired enzyme" electrodes.[16, 17]

The ligand exchange, and therefore the electrodeposition, takes place only when the surface coverage by the precursor redox polymer is high. When the precursor polymer does not densely cover the surface, the likelihood of finding neighboring chains at distances short enough for ligand exchange is small. Chloride, a weakly coordinating anionic ligand, is exchanged when $Os^{3+}$ is electroreduced to $Os^{2+}$ thereby diminishing the coulombic component of the binding energy. As the rate of interchain ligand exchange increases with the surface density of the chain containing the exchanged ligand and with that of the chain containing the exchanging ligand, it scales superlinearly with the surface density of the adsorbed polymer. At high surface coverage, the crosslinking is expected to be rapid and at low coverage it is expected to be negligible. The surface density of adsorbed redox polycations can be modulated on vitreous carbon electrodes through their oxidation, because oxidation of the carbon surface adds polycation-binding carboxylate and phenolate functions.[18]

On vitreous carbon electrodes that were pre-oxidized in plasma (air, 1 Torr, 5 min) the redox polymers were electrodeposited under exceptionally mild conditions, merely by cycling the electrodes between −150 and +150 mV vs the polymer's redox potential. When the vitreous carbon electrodes were not oxidized in plasma, the electrodeposition required electrooxidation of their surfaces and did not proceed unless the electrodes were cycled to greater than +0.4 V prior to applying the crosslinking reducing potential. The rate of deposition increased when the oxidizing potential was raised up to 0.8 V (vs Ag/AgCl; Figure 1). Thus, the purpose of the oxidative half cycle, where the electrode surface is oxidized, is to increase the surface density of the redox polymer prior to its crosslinking in the reductive half cycle.

Crosslinked films of redox polymer **I** (Scheme 1) were irreversibly electrodeposited from redox polymer solutions in PBS (0.5–1.0 mg mL$^{-1}$ polymer, pH 7.1, 20 mM phosphate buffer, 0.1M NaCl solution). In the 200-s process the potential was stepped 50 times between −0.3 (2 s) and +0.8 V (2 s). A sequence of the applied square potential waves is illustrated in

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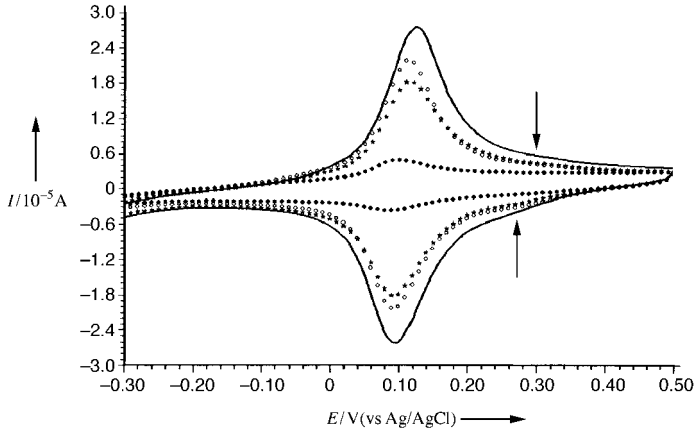


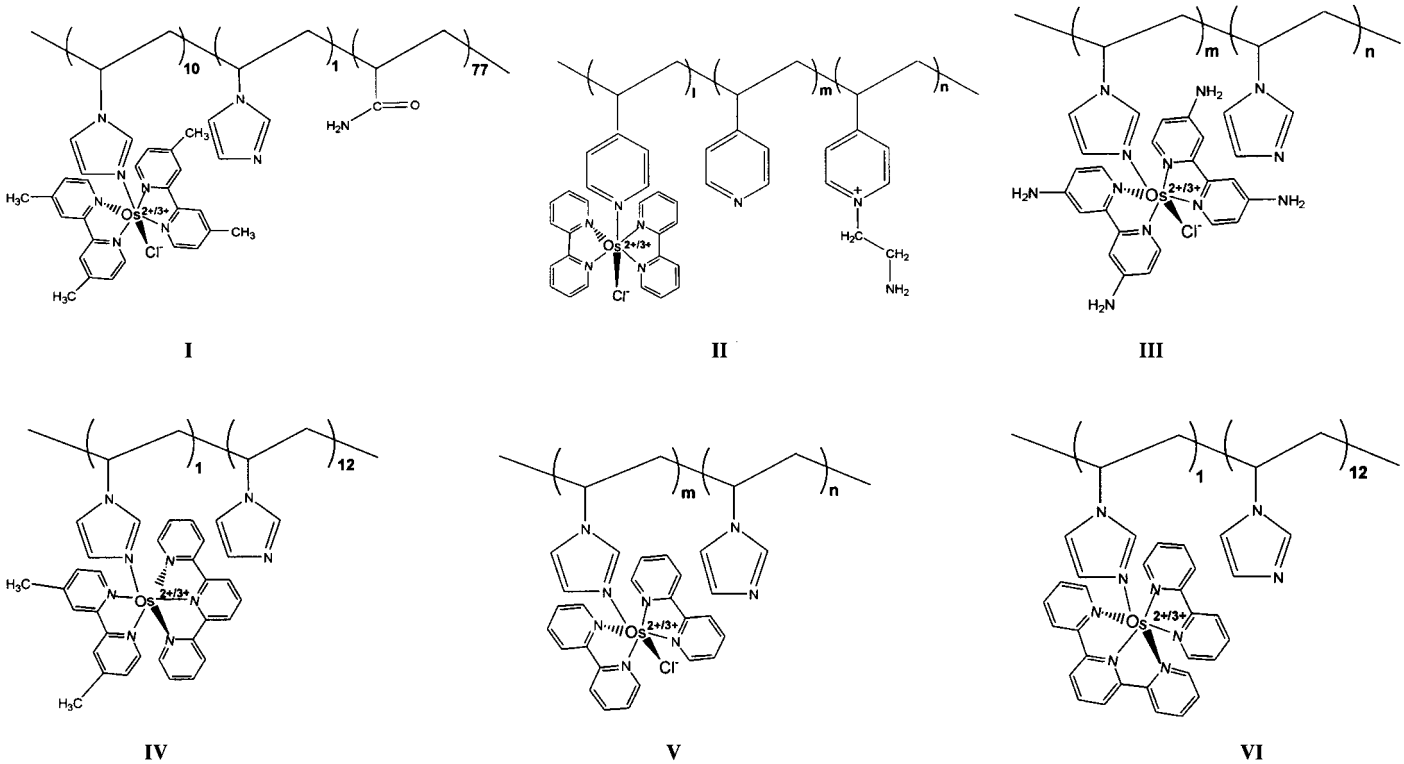

Figure 1. Dependence of the cyclic voltammograms of **I** on the oxidizing potential applied in its deposition. The reducing potential was fixed at −0.3 V. Oxidizing potential: 0.40 (●), 0.60 (∗), 0.70 (○), and 0.80 V (——). pH 7.1, PBS buffer, 100 mV s$^{-1}$, 50 square waves. Note the difference between the left and right branches of the voltammetric waves, resulting of the formation of crosslinking $Os^{2+/3+}$ centers, the redox potential of which is higher. The approximate positions of the peaks of the waves of the crosslinking centers are marked with arrows.

the insert of Figure 3. In the case of redox polymer **I**, integration of the cyclic voltammograms showed coverage by about $10^{-9}$ mol redox centers per cm$^2$. The exchange of $Cl^-$ by imidazole or pyridine added small, embedded voltammetric waves, making the tails of the voltammograms of the electrodeposited films asymmetrical: The currents of their positive (right-side) branches exceeded those of their negative (left-side) branches.

Because the crosslinking Os centers have six heterocyclic nitrogen atoms in their inner coordination sphere, their redox potential is shifted to more positive values relative to the potential of the noncrosslinking Os centers, which remain coordinated by $Cl^-$ and five hetrocyclic nitrogen atoms. The shift is about 200 mV when the exchanging ligand is an imidazole function and about 250 mV when the exchanging ligand is a more strongly coordinating pyridine function.[19, 20] The approximate positions of the embedded peaks associated with the Os centers coordinated by six nitrogen atoms are marked in Figures 1 and 2 by arrows. The maximal current difference between the right and left branches of the voltammograms (associated with the centers coordinated by six nitrogen atoms) and the peaks associated with the centers coordinated by five nitrogen atoms and one chloride shows that upon electrodeposition about 5–10% of the Os centers exchanged $Cl^-$ ions by heterocyclic nitrogen atoms.

The waves of the voltammograms of the freshly electrodeposited films of **I** narrowed in the first 20 electrooxidation/reduction cycles. Their peak heights increased linearly with the scan rate up to 500 mV s$^{-1}$; at small scan rates the peaks of the reduction and oxidation waves were separated by less than 10 mV (Figure 2).[21] When **I** was electrodeposited from its solution in PBS (0.5 mg mL$^{-1}$), the thickness of the electroactive films increased linearly with the number of cycles in the first 50 (2+2)-s cycles; it increased less and nonlinearly between 50 and 200 cycles; and at >200 cycles the thickness no longer increased (Figure 3).

As seen from Table 1, persistent films were electrodeposited only from solutions of those redox polymers that contain uncoordinated imidazole or pyridine ligands and Os complexes with inner-sphere $Cl^-$: Polymers **IV** and **VI** have no inner-sphere $Cl^-$ and are not deposited; polymers **I**, **II**, **III**, and **V** do have inner-sphere $Cl^-$ and are electrodeposited.




Scheme 1. Structures of the redox polymers studied.

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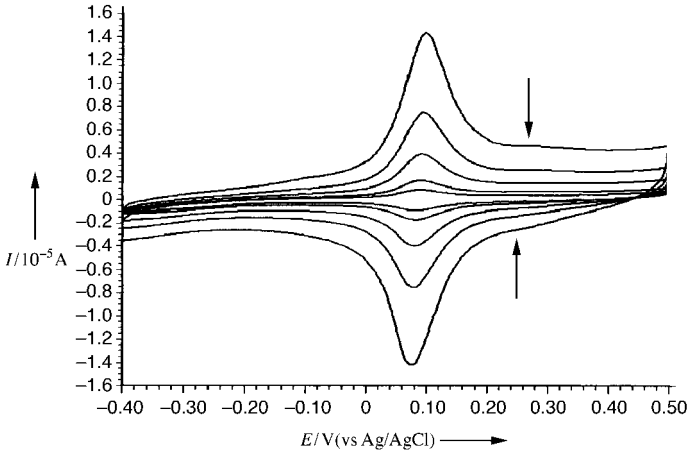


Figure 2. Cyclic voltammograms of the fully annealed film of **I** on vitreous carbon. pH 7.1, PBS buffer. Scan rates from the innermost to the outermost waves: 10, 20, 50, 100, and 200 mV s$^{-1}$. The approximate positions of the peaks of the waves of the crosslinking centers are marked with arrows.

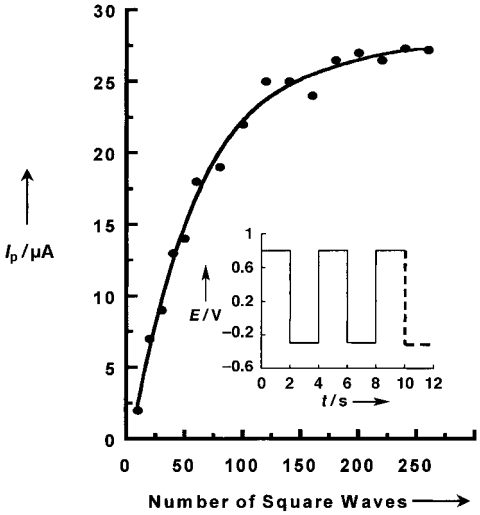


Figure 3. Dependence of the voltammetric peak current $I_p$ on the number of square waves applied. Insert: A sequence of the square potential waves applied in the electrodeposition.

It had been recognized earlier that $Ru^{2+}$ complexes containing labile ligands, for example aqua complexes, are readily bound to proteins by exchanging their labile ligand with a protein-bound histidine.[22–24] Because histidine, lysine, and arginine functions coordinate also to $Os^{2+}/Os^{3+}$, enzymes were readily co-electrodeposited with the redox polymers. Co-electrodeposition of redox polymers (0.50 mg mL$^{-1}$) and glucose oxidase (GOX), horseradish peroxidase (HRP), soybean peroxidase (SBP), or laccase (0.50 mg mL$^{-1}$) at room temperature from solutions with pH (7.2 ± 0.1) yielded electrocatalytic films, on which the substrates of the enzymes were selectively electrooxidized/reduced. Thus glucose was electrooxidized on electrodes with **I** and co-deposited GOX;[25] $H_2O_2$ was electroreduced on electrodes with **I** and co-deposited HRP or SBP; and $O_2$ was electroreduced on electrodes with co-deposited laccase. The cyclic voltammograms of the GOX and the SBP electrodes are shown in Figure 4. As in the case of the pure redox polymer films, the redox polymer–enzyme films also have rapidly electron-exchanging redox couples: At scan rates up to 100 mV s$^{-1}$, the separation of the peaks of the voltammetric electroreduction and electrooxidation waves is less that 10 mV for the enzyme electrodes, and almost no hysteresis is observed at a scan rate of 10 mV s$^{-1}$ (Figure 4).

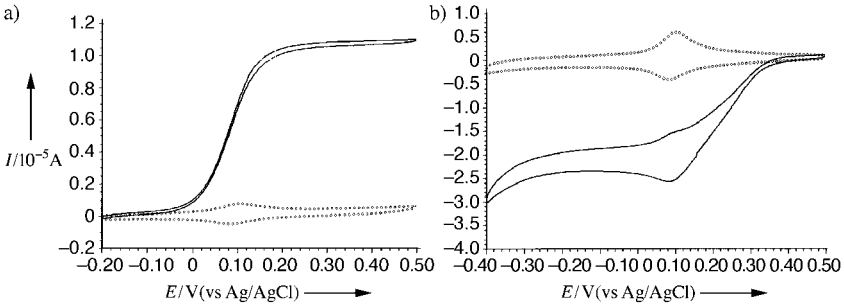


Figure 4. a) Cyclic voltammograms of **I** with co-electrodeposited GOX in PBS buffer: no glucose (○), 20 mM glucose (——). b) Cyclic voltammograms of **I** with co-electrodeposited SBP in PBS buffer: no $H_2O_2$ (○), 1.0 mM $H_2O_2$ (——). 3-mm vitreous carbon electrodes, pH 7.1, scan rate 5 mV s$^{-1}$.

To prove that the glucose oxidase was coordinatively bound to the redox polymer, not entrapped in it, an ultrathin (about one polymer monolayer thick) film of polymer **I** and glucose oxidase was electrodeposited by applying a single (2+2)-s pair of square waves. The enzyme was not leached from the ultrathin film when the electrode was rotated at 500 rpm in a buffered glucose solution: The negative branch of the voltammogram was totally absent, as it was in the voltammogram of the electrode on which a film 50 times thicker was deposited (Figure 4).

While the reaction centers of glucose oxidase that have been reduced by glucose cannot be directly electrooxidized on carbon electrodes, oxidized reaction centers of adsorbed soybean peroxidase and of laccase might be directly electroreduced on films comprising small graphite particles. To test for possible catalysis by soybean peroxidase directly adsorbed at the uncoated vitreous carbon electrode, the electrode was

Table 1. Examples of electrodeposited and non-electrodeposited redox polymers.

| Polymer | Film deposition | $E^{ox}_{1/2}$ [mV] (solution) | $E^{ox}_{1/2}$ [mV] (film) | Coverage, $\Gamma \times 10^{10}$ mol cm$^{-2}$ | Film |
|---|---|---|---|---|---|
| **V** | yes | −10 | 20 | 4.2 | stable |
| **VI** | no | 545 | – | – | – |
| **IV** | no | 550 | – | – | – |
| **III** | yes | −130 | −90 | 6.2 | stable |
| **II** | yes | 325 | 340 | 7.8 | stable |

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soaked in a soybean peroxidase solution (25 mg mL$^{-1}$) for 2 h, rinsed and its voltammogram was measured in a buffered $H_2O_2$ solution (2 mM). Comparison of the voltammogram with that of an electrode that was not immersed in the soybean peroxidase solution showed no measurable difference. Furthermore, while $H_2O_2$ is catalytically electroreduced already at a potential as positive as +0.35 V vs Ag/AgCl on the electrode with the co-electrodeposited film of soybean peroxidase and **I**, electroreduction of $H_2O_2$ was not observed on the vitreous carbon electrode exposed to the soybean peroxidase solution at potentials positive of −0.08 V vs Ag/AgCl, ruling out the possibility that the reduction of hydrogen peroxide is catalyzed by directly adsorbed soybean peroxidase.

The results show that four conditions must be met for a crosslinking and an electro-deposition of redox polymers based on ligand exchange: first, the film must be electron- or hole-conducting, otherwise only an insulating, necessarily very thin film is deposited; second, the redox centers of the deposited polymer that are based on transition metal complexes must contain in their inner coordination sphere a labile ligand; third, the redox polymer must contain in its backbone a strongly coordinating but yet uncoordinated ligand; fourth, because neighboring chains exchange ligands in the crosslinking process, the surface density of the adsorbed redox polymer must be high, otherwise the fraction of crosslinked polymer will be small.

### *Experimental Section*

$[Os(bpy)_2Cl_2]$ (bpy = 2,2′-bipyridine) was synthesized from $K_2OsCl_6$ by the procedure of Lay et al.[26] The syntheses of the redox polymers is shown in Scheme 1, poly(4-vinylimidazole-co-acrylamide) partially complexed with $[Os(bpy)_2Cl]^+/[Os(bpy)_2Cl]^{2+}$ (**I**),[27] poly(4-vinylpyridine) partially complexed with $[Os(bpy)_2Cl]^+/[Os(bpy)_2Cl]^{2+}$ and partially quaternized with 2-bromoethylamine (to increase its solubility in water, **II**),[25] poly(*N*-vinylimidazole) partially complexed with $[Os(4,4'\text{-diamino-}2,2'\text{-bipyridine})_2Cl]^+/[Os(4,4'\text{-diamino-}2,2'\text{-bipyridine})_2Cl]^{2+}$ (**III**),[28] poly(*N*-vinylimidazole) partially complexed with $[Os(4,4'\text{-dimethyl-}2,2'\text{-bipyridine})(terpyridine)]^{2+}/[Os(4,4'\text{-dimethyl-}2,2'\text{-bipyridine})(terpyridine)]^{3+}$ (**IV**),[20] poly(*N*-vinylimidazole) partially complexed with $[Os(bpy)_2Cl]^+/[Os(bpy)_2Cl]^{2+}$ (**V**),[19] and poly(*N*-vinylimidazole) partially complexed with $[Os(bpy)(terpyridine]^{2+}/[Os(bpy)(terpyridine]^{3+}$ (**VI**)[28] were described earlier. Glucose oxidase (GOX, EC 1.1.3.4, Type X-S, from *Aspergillus niger*, 213 units mg$^{-1}$ of solid) was purchased from Fluka (Fluka Chime AG, Buchs). Horseradish peroxidase (HRP, EC 1.11.1.1, Type VI, 330 units mg mg$^{-1}$) and laccase (EC 1.10.3.2, 180 units mg$^{-1}$) were purchased from Sigma Chemical Co. (St. Louis, MO), and soybean peroxidase (SBP, HP grade, 130 pyrogallol units mg$^{-1}$) was purchased from Enzymol International, Inc. The phosphate-buffered saline solution (PBS) (pH 7.1, 0.15 M NaCl, 0.02 M phosphate) was freshly prepared using deionized water.

3-mm diameter vitreous carbon electrodes were used. They were polished with alumina, rinsed with deionized water and cycled between −0.4 and +0.8 V in PBS buffer until the featureless voltammograms of sequential cycles were identical. The electrochemical experiments were carried out using a CH Instruments Model 832 electrochemical detector (CH Instruments, Austin, TX). The three-electrode cell had a glassy carbon working electrode, a BAS micro Ag/AgCl reference electrode and a platinum foil counter electrode. The electrodes were placed in a homemade 1.0-mL electrochemical cell. An Analytical Rotator (Pine Instrument Company, Grove City, PA) was used to control mass transport. All reported potentials are referred to the Ag/AgCl (3 M NaCl) reference electrode.

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