SUMMARY OF THE INVENTION

To address the needs in the art, a method for extracting metal ions from water that includes disposing two electrically conductive electrodes in water, where the water includes a target ion species in solution, where at least one of the electrically conductive electrodes is a functionalized electrode having species-specific adsorption of the target ion species, and providing electrical current to the electrically conductive electrodes such the one or more target ion species are deposited to metallic form or metal oxides at the functionalized electrode by one or more electrochemical reactions.

According to one aspect of the invention, the electrical current includes an alternate current or direct current.

In another aspect of the invention, the conductive electrodes are carbon-based materials include carbon felt, carbon fibers, carbon nanotubes, carbon blacks, activated carbon, graphite plates, graphene, or graphene oxides.

According to a further aspect of the invention, the electrodes are functionalized with amidoxime-based chemicals.

In yet another aspect of the invention, a voltage across the electrodes alternates between a negative value and zero.

According to one aspect of the invention, the water includes seawater, lake water, river water, domestic wastewater, industrial wastewater or drinking water.

According to one aspect of the invention, the target ion species can include uranium, vanadium, copper, silver, gold, cadmium, lead, mercury, cobalt, rhodium, iridium, nickel, palladium, platinum, and rare earth metals.

In another aspect of the invention, where all the target ions are randomly distributed in the aqueous solution, where when a negative bias is applied, the target ions will start to migrate according to an external electrical field, where an electrical double layer on the surface of the functionalized electrode is formed, where the target ions in an inner layer of the electrical double layer form chelation binding to a surface of the functionalized electrode, where a metallic species of the target ion is reduced and electrodeposited as a charge neutral species to the functionalized electrode, where when the bias is removed the target ions and the electrodeposited target metallic species are left attached to the functionalized electrode surface, where other ions without specific binding are redistributed on the functionalized electrode surface and released from surface active sites, where as the negative bias repeats, more target ions will attach to the functionalize electrode surface and the electrodeposited target metallic species are further deposited to grow into bigger particles relative to the target ion.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1A-1D show schematic views of the physicochemical and HW-ACE extraction;: (**1A**) coulomb repulsion in the physicochemical adsorption, where the adsorbed charged ions can reject incoming ions; (**1B**) competition between uranyl ions and other cations that reduces the adsorption of uranyl ions and

area. Moreover, the alternating manner of the applied voltage can prevent unwanted cations from blocking the surface active sites and also avoid water splitting. As a result, the HW-ACE method achieves a 9-fold higher uranium extraction capacity (1932 mg/g) without saturation and 4-fold faster kinetics than conventional physicochemical methods, as well as high selectivity inherited from the amidoxime functionalization.

In general, the method according to the current invention relies on electrochemical deposition to extract/remove ions from water combined with appropriately functionalized electrodes. According to embodiments of the invention, a pair of conducting electrodes (carbon or metal mesh/foam based with functional coatings) is used for metal ions to be deposited on. The surface functionalization of an electrode (polymers, graphene oxide, etc.) is provided to increase the selectivity to certain metal ions while still providing electrical conductivity. Also the electrochemical potentials (bias) and frequency can be tuned to only deposit certain metal ions.

According to one example, uranium extraction from seawater is accomplished by a half-wave rectified alternating current electrochemical reaction. Here an alternating voltage is used to extract uranium (as uranyl ions) from seawater. In this example embodiment, the electrode used is an Amidoxime functionalized carbon felt electrode.

According to one aspect of the invention, the electrical current includes an alternate current or direct current.

In another aspect of the invention, the conductive electrodes are carbon-based materials

include carbon felt, carbon fibers, carbon nanotubes, carbon blacks, activated carbon, graphite plates, graphene, or graphene oxides.

According to a further aspect of the invention, the electrodes are functionalized with amidoxime-based chemicals.

In yet another aspect of the invention, a voltage across the electrodes alternates between a negative value and zero.

According to one aspect of the invention, the water includes seawater, lake water, river water, domestic wastewater, industrial wastewater or drinking water.

According to one aspect of the invention, the target ion species can include uranium, vanadium, copper, silver, gold, cadmium, lead, mercury, cobalt, rhodium, iridium, nickel, palladium, platinum, and rare earth metals.

In another aspect of the invention, where all the target ions are randomly distributed in the aqueous solution, where when a negative bias is applied, the target ions will start to migrate according to an external electrical field, where an electrical double layer on the surface of the functionalized electrode is formed, where the target ions in an inner layer of the electrical double layer form chelation binding to a surface of the functionalized electrode, where a metallic species of the target ion is reduced and electrodeposited as a charge neutral species to the functionalized electrode, where when the bias is removed the target ions and the electrodeposited target metallic species are left attached to the functionalized

electrode surface, where other ions without specific binding are redistributed on the functionalized electrode surface and released from surface active sites, where as the negative bias repeats, more target ions will attach to the functionalize electrode surface and the electrodeposited target metallic species are further deposited to grow into bigger particles relative to the target ion.

A second example is provided that includes heavy metal removal by electrochemical deposition. Here a DC voltage is applied between two conducting electrodes (carbon felt with graphene oxide or carbon felt with amidoxime polymer). During operation, the trace amount of hazardous heavy metal ions are deposited on the negative electrode.

This current invention can be applied to extract valuable metal resources from seawater such as uranium, vanadium, copper, etc. This technology can also be applied to remove heavy metal ions such as cadmium, copper, lead, mercury, etc. from drinking water.

Significant advantages include providing a significantly larger extraction capacity than traditional physiochemical adsorption. The electrochemical extraction according to the current invention has a capacity above ~2000 mg/g without saturation, compared to a 100-200 mg/g capacity based on traditional physiochemical adsorption. The current invention offers faster kinetics than traditional physicochemical adsorption. The applied voltage introduces an electric field in the system, where ions migrate according to the electric field to find the electrode surface more easily than random diffusion. A further advantage of this technology is an increased lifetime of the materials used and a reduction in the potential damage to the material during recycling with same amount of initial material use. The

CLAIMS

What is claimed:

1. A method for extracting metal ions from water, comprising:

a) disposing two electrically conductive electrodes in water, wherein said water comprises a target ion species in solution, wherein at least one of the electrically conductive electrodes is a working electrode having species-specific adsorption of said target ion species, wherein the working electrode is functionalized with amidoxime-based chemicals; and

b) providing electrical current to said electrically conductive electrodes such that the one or more target ion species are deposited to metallic form or metal oxides at said working electrode by one or more electrochemical reactions.

2. The method according to claim 1, wherein said electrical current comprises an alternate current or direct current.

3. The method according to claim 1, wherein the working electrode comprises one of carbon felt, carbon fibers, carbon nanotubes, carbon blacks, activated carbon, graphite plates, graphene, or graphene oxides.

4. The method according to claim 1, wherein a voltage across said electrodes alternates between a negative value and zero.

5. The method according to claim 1, wherein said water comprises seawater, lake water, river water, domestic wastewater, industrial waste water or drinking water.

6. The method according to claim 1, wherein said target ion species is selected from the group consisting of uranium, vanadium, copper, silver, gold, cadmium, lead, mercury, cobalt, rhodium, iridium, nickel, palladium, platinum, and rare earth metals.

7. The method according to claim 1,

wherein all said target ions are randomly distributed in the aqueous solution,

wherein when a negative bias is applied, said target ions migrate according to an external electrical field,

wherein an electrical double layer on a surface of said working electrode is formed in response to the external electrical field,

wherein said target ions in an inner layer of the said electrical double layer form chelation binding to the surface of said working electrode,

wherein a metallic species of said target ion is reduced and electrodeposited as a charge neutral species to said working electrode,

wherein when the bias is removed said target ions and said electrodeposited target metallic species are left attached to said working electrode surface, and wherein other ions without specific binding are redistributed on said working electrode surface and released from surface active sites, and

wherein as said negative bias repeats, more target ions attach to said working electrode surface and said electrodeposited target metallic species are further deposited to grow into bigger particles relative to said target ion.