

A Memristor Comprising a Protein and a Method of Manufacturing Thereof

Cross-Reference To Related Application

[0001] This application makes reference to and claims the benefit of priority of an application for "Memristor Nanodevices Based on Proteins" filed on October 15, 2010, with the United States Patent and Trademark Office, and there duly assigned serial number 61/393,523. The content of said application filed on October 15, 2010, is incorporated herein by reference for all purposes, including an incorporation of any element or part of the description, claims or drawings not contained herein and referred to in Rule 20.5(a) of the PCT, pursuant to Rule 4.18 of the PCT.

Technical Field

[0002] Various embodiments relate to the field of memristors, in particular memristors comprising proteins.

Background

[0003] Memristor is regarded as the fourth fundamental two-terminal circuit element following resistor, capacitor, and inductor. It has attracted increasing research interest, owing to its potential application in next generation memory storage.

[0004] Programmable conductivity switches between high resistance state (OFF state) and low resistance state (ON state) are realized as memristive, which are seen to have a wide use in electronic industry in future. Various materials, such as metal oxides or chalcogenides, amorphous silicon or carbon, and polymer-modified nanoparticles have been employed. Memristive devices are being developed for application in nanoelectronic memories, computer logic, and neuromorphic computer architectures. However, natural biomaterials in exploitation of memristor nanodevices have not been reported so far. Natural biomaterials have much better biocompatibility than all of the artificially synthesized materials. Therefore, biomaterial-based nanodevices can be used in designing

more complex and functional nanocircuits for biomedical and biodiagnostic applications.

[0005] It has been demonstrated that some natural proteins, especially the redox proteins, can also be used as electronic materials to obtain solid-state electron transport junctions.

[0006] Nanogaps can be generated using On-Wire Lithography (OWL), which is based on electrochemical deposition of multisegmented nanorods and selective chemical etching of sacrificial segments. Using OWL, the width of the nanogaps generated can be tuned from about a few micrometers to about 2 nm.

[0007] Protein transport junctions can be assembled within nanogaps to explore new suitable biomaterials for memory storage in electronic industry and contemporaneously understand the natural conductance of various redox proteins.

[0008] Ferritin, the main intracellular iron storage protein which is employed as a bionanomaterial in material science and chemistry, has been found to exhibit a very high stability. This characteristic is due to the particular structure of the protein, a nearly spherical shell (~12 nm) and an active center of hydrous ferric oxide mineral as a core. The shell can be used as a template for synthesis of nanoparticles while the core is the key factor for electron transfer of ferritin in electrochemical analysis. In addition, ferritin can withstand a pH ranging from about 2.0 to about 12.0 and high temperatures about 80 °C. These are advantageous properties of a natural biomaterial that is to be used to fabricate electronic devices.

[0009] It is an object of the present invention to provide a biomolecule-based memristor showing biological “memory” storage based on the mechanism of iron uptake and release.

Summary of the Invention

[0010] In a first aspect, the present invention relates to a memristor comprising two electrically conducting terminals arranged with a nanometer-scaled gap therebetween, and a protein disposed in the gap to form a protein-based transport junction between the two electrically conducting terminals, wherein the protein is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a

change in bias voltage applied across the two electrically conducting terminals.

[0011] In a second aspect, a method of fabricating a memristor is provided. The method comprises preparing a nanometer-scaled gap between two electrically conducting terminals, and disposing a protein in the gap to form a protein-based transport junction between the two electrically conducting terminals, wherein the protein is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a change in bias voltage applied across the two electrically conducting terminals.

Brief Description of the Drawings

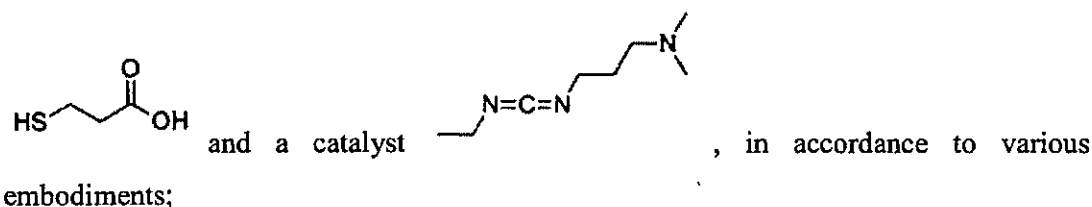
[0012] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0013] Figure 1 shows a schematic block diagram of a memristor, according to various embodiments;

[0014] Figure 2 shows a schematic block diagram of a memristor, according to various embodiments;

[0015] Figure 3 shows a schematic block diagram of a method of fabricating the memristor, according to various embodiments;

[0016] Figure 4 shows (a) SEM image of a device prepared with an OWL-fabricated wire with a ~12 nm gap; (b) its expanded view as enclosed by the marked rectangular area; (c) a scheme of the fabrication of the ferritin-based ~12nm device; and (d) a chemical representation of the interaction between Au and ferritin involving a link



[0017] Figure 5 shows representative I - V characteristics of ~ 12 nm OWL-generated gaps before and after assembly of ferritin (scan for 5 five times under vacuum), in accordance to various embodiments;

[0018] Figures 6a to 6d shows The current-voltage characteristics for four different about 12 nm gap devices loaded with ferritin (measured in vacuum), in accordance to various embodiments;

[0019] Figure 7 shows current response of a ferritin-based nanogap device to applied biases during the tests of write-read-erase cycle (1 V for writing, 0.6 V for reading, and -1 V for erasing), in accordance to various embodiments;

[0020] Figure 8a shows representative I - V characteristics of apoferritin-modified ~ 12 nm OWL-generated gaps before and after reconstitution of iron core (scan for 5 five times under vacuum) inside apoferritin shells, in accordance to various embodiments;

[0021] Figure 8b shows I - V curves of OWL-generated nanogaps before and after assembly of apoferritin, in accordance to various embodiments;

[0022] Figure 9 shows the current-voltage characteristics for about 12 nm gap device loaded with ferritin (measured in air), in accordance to various embodiments;

[0023] Figure 10 shows the current-voltage characteristics for about 12 nm gap device loaded with apoferritin before and after added with iron ion (measured in vacuum), in accordance to various embodiments; and

[0024] Figure 11 shows I - V responses of ferritin-modified the ~ 12 nm nanogap fabricated by OWL in different temperatures, in accordance to various embodiments.

Detailed Description

[0025] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new

embodiments.

[0026] Figure 1 shows a schematic block diagram of a memristor, according to various embodiments. In a first aspect, a memristor 100 is provided. The memristor 100 comprises two electrically conducting terminals 102 arranged with a nanometer-scaled gap 104 therebetween, and a protein 106 disposed in the gap 104 to form a protein-based transport junction between the two electrically conducting terminals 102, wherein the protein 106 is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a change in bias voltage applied across the two electrically conducting terminals 102.

[0027] “Reversibly switchable between two electronic states” means that the element or in this case, the protein 106 can change from a first electronic (or quantum) state to a second electronic (or quantum) state due to a first condition; and can change from the second electronic (or quantum) state to the first electronic (or quantum) state due to a second condition. As an example, the protein 106 may change from ground state (i.e., the state with lowest energy) to an excited state (i.e., a state with higher energy) when biased at, for example, a negative voltage; and may change from the excited state to the ground state when biased at, for example, a positive voltage. The change (or switching) of the states may be repeatable.

[0028] “Protein”, as used herein, refers to a polymer of amino acids that may consist of one or more polypeptide chains. Each of the polypeptides chains forming the protein may consists of at least 100 amino acids. The amino acids may be selected from the natural occurring amino acids, including glycine, alanine, valine, leucine, isoleucine, phenylalanine, tyrosine, tryptophan, proline, serine, threonine, asparagine, glutamine, aspartic acid, glutamic acid, histidine, lysine, arginine, cysteine and methionine. The protein may also comprise non-natural or artificial amino acids.

[0029] In the context of various embodiments, the term “transport junction” may generally refer to a barrier controlling the flow of ion and electrons between two terminals by allowing or disallowing ions and electrons to pass through; thereby establishing or breaking conducting flow, respectively.

[0030] According to various embodiments, the protein 106 may comprise a redox

protein. As used herein, a redox protein may refer to a protein that catalyzes the transfer of electrons from one molecule (the reductant, also called electron donor) to another (the oxidant, also called electron acceptor). For example, a redox protein may be an enzyme or an oxidoreductase.

[0031] In various embodiments, the protein 106 may comprise a protein having a metal oxide core. Examples of the protein 106 may be selected from the group consisting of ferritin, transferrin, lactoferrin, and a mixture thereof. Also included are mutants of said afore-mentioned proteins, for example those that have been engineered to have a higher stability or improved redox properties. The protein 106 may also be a ferritin selected from the Interpro protein database entry IPR001519.

[0032] According to various embodiments, the protein-based transport junction may be configured to switch from the high resistance state to the low resistance state by applying a first predetermined bias voltage across the two electrically conducting terminals 102. The first predetermined bias voltage may be about +0.7 V to about +3 V.

For example, the first predetermined bias voltage may be about +0.7 V.

[0033] In various embodiments, the protein-based transport junction may be configured to switch from the low resistance state to the high resistance state by applying a second predetermined bias voltage across the two electrically conducting terminals 102. The second predetermined bias voltage is about -0.8 V to about -3 V.

For example, the second predetermined bias voltage is about -0.8V.

[0034] The memristor 100 may be configured to exhibit a resistance hysteresis at bias voltages lower than -0.8 V or higher than +0.7 V when applied across the two electrically conducting terminals 102.

[0035] The memristor 100 may express a non-volatile resistance change.

[0036] In various embodiments, the memristor 100 may be configured to perform a reading operation by applying a reading voltage across the two electrically conducting terminals 102 and obtaining a current value in the high resistance state or in the low resistance state. The reading voltage may be about +0.6 V to about -0.7 V. For example, the reading voltage may be about +0.6 V.

[0037] In Figure 2, various embodiments provide the memristor 100 may further comprise a substrate 200, on which the two electrically conducting terminals 102 are

disposed. The substrate 200 may be made of any materials with the properties of insulation, flat surface, and chemical inert, for example, quartz or glass. The substrate 200 may be made of Si or Si/SiO₂.

[0038] The two electrically conducting terminals 102 may be made of any chemically stable and conductive metals. In various embodiments, each of the two electrically conducting terminals 102 may be made of a material selected from the group consisting of gold (Au), chromium (Cr), platinum (Pt), titanium (Ti), palladium (Pd), silver (Ag), copper (Cu), aluminum (Al), tungsten (W) and an alloy thereof. In a further embodiment, the two electrically conducting terminals 102 may be made of the same material. In another embodiment, the two electrically conducting terminals 102 may be made of different materials.

[0039] In the context of various embodiments, the term “gap” may generally refer to a space or spacing located between two terminals. Such a space may be physically described as a volume bounded at least by the areas of the respective terminal surfaces in whole or part thereof. Depending on the geometry of the gap 104, the length measured across one terminal surface to the other terminal surface may be referred to as the width of the gap 104 or interchangeably referred to as the average width.

[0040] In various embodiments, the gap 104 may have a width of about 2 nm to about 100 nm.

For example, the gap 104 may have a width of about 12 nm. This width of the gap 104 may be amenable to the assembly of protein molecules across such gaps. Moreover, under such system, a protein-based single-rod nanodevice can be achieved.

[0041] Figure 3 shows a schematic block diagram of a method of fabricating the memristor, according to various embodiments. In a second aspect, a method of fabricating a memristor 300 is provided. The method 300 comprises preparing a nanometer-scaled gap between two electrically conducting terminals 302, and disposing a protein in the gap to form a protein-based transport junction between the two electrically conducting terminals 304, wherein the protein is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a change in bias voltage applied across the two electrically conducting terminals.

[0042] In various embodiments, the proteins are as defined above.

[0043] In various embodiments, preparing the nanometer-scaled gap between the two electrically conducting terminals 302 may comprise synthesizing a multisegment nanostructure comprising a nanometer-scaled sacrificial layer formed between electrically conducting materials for the terminals, and removing the sacrificial layer from the multisegment nanostructure; thereby forming the nanometer-scaled gap between the two electrically conducting terminals.

[0044] Synthesizing the multisegment nanostructure may comprise electrochemically depositing the electrically conducting materials and the sacrificial layer therebetween in a membrane template. For example, the membrane template may comprise an anodized aluminumoxide (AAO) membrane template. The membrane template may have an average pore size of about 360 nm.

[0045] In various embodiments, the nanostructure may comprise a nanorod.

[0046] In these embodiments, the electrically conducting materials are as defined above for the electrically conducting terminals.

[0047] According to various embodiments, removing the sacrificial layer may be performed by etching means. The sacrificial layer may be made of nickel.

[0048] In various embodiments, disposing the protein in the gap 304 comprises mixing the two electrically conducting terminals arranged with the nanometer scaled gap therebetween with a buffer of protein and a crosslinking agent for about 6 hours to about 20 hours. The crosslinking agent may be selected from the functional group of carbodiimides. The crosslinking agent may be selected from the group consisting of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC), *N,N'*-dicyclohexylcarbodiimide, *N,N'*-diisopropylcarbodiimide, and a derivative thereof. Here, for example, EDC may be used as the catalyst for the formation of chemical bond between carboxyl group and amine group.

[0049] In various embodiments, the method 300 may further comprise coupling the nanostructure to a microelectrode, prior to disposing the protein in the gap. The nanostructure may be coupled to the microelectrode by e-beam lithography and subsequent chromium and gold thermal deposition. The microelectrode may be obtained by thermally evaporating chromium and gold onto a resist-patterned wafer, followed by

incubating the wafer and subsequently by removing the resist from the wafer.

[0050] In various embodiments, the gap may be covalently modified with 3-mercaptopropionic acid (MPA) to facilitate covalent coupling of the protein.

[0051] The protein may be randomly and colvanly assembled within the gap.

[0052] Covalent bonding ensures strong electronic coupling between the proteins and electrodes. This kind of covalent assembly is based on the chemical bond between the carboxyl group of the linker on the electrode and the amine group of the protein molecules, so the orientation of the protein molecules inside the gap is dependent on the structure of the protein, more specifically, the distribution of the amine group on the surface of the protein.

[0053] Non-covalent immobilization, such as electrostatic attraction, of the proteins to the electrodes may also be possible. However, the electron transport in such a device may be affected and not as effective as compared to the covalent assembly.

[0054] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a variance of +/- 5% of the value.

[0055] The phrase “at least substantially” may include “exactly” and a variance of +/- 5% thereof. As an example and not limitation, the phrase “A is at least substantially the same as B” may encompass embodiments where A is exactly the same as B, or where A may be within a variance of +/- 5%, for example of a value, of B, or vice versa.

[0056] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

Examples

[0057] A single-rod electrical device based on ferritin assembled within OWL-generated ~12 nm gap has been fabricated. This two-terminal ferritin device performs a controllable and stable resistive switching under continuous low bias as a memristor. The natural biomolecule has been available integrated to functional electrical device and thereby this ferritin-based memristor have much better biocompatibility than all of the artificially

synthesized materials, and may be as a key unit to apply to biomedical and clinical fields in future research.

Materials and Methods

[0058] Preparation of OWL-generated nanogap

[0059] First, Au-Ni-Au multisegmental nanorod were synthesized via electrochemical deposition of gold, nickel, and gold plating solution (Orotemp 24 RTU and Nickel sulfamate RTU, Technic Inc., Cranston, RI, USA) in anodized aluminumoxide (AAO) membrane (0.02, cat. no. 6809-5002, Whatrman Inc. Maidstone, UK) template (pore diameter of about 360 nm) with electrochemical station (EC epsilon, BASi, West Lafayette, IN, USA). Trough controlling the charge (120 mC) during the electrochemical deposition of nickel, a approximately 12 nm nickel layer was obtained. After etching such sacrificial layer of Ni by 1M HCl for about 3 hours, ~12 nm nanogap was generated for assembly of ferritin monolayer inside.

[0060] Photolithography and E-beam Lithography

[0061] Si wafers with 600 nm SiO₂ layer were cleaned via sonicating in acetone and ethanol for about 30 mins, rinsed with ethanol and dried with N₂. After the spin coating with a photoresist (AZ 1518 Photoresist, Shipley, USA) at about 3000 rpm for about 30 s, the wafers were put in an oven (about 95 °C) for about 5 mins. The resist was subsequently patterned using a mask aligner (SUSS MJB4 Mask Aligner, Garching, Germany) and developed with AZ 300 MIF. Then, Cr (5 nm) and Au (50 nm) were thermally evaporated onto the patterned wafer. Finally, after the patterned wafer was immersed in acetone for liftoff, the microelectrodes were formed.

[0062] A suspension of gold nanorods with OWL-fabricated nanogaps was deposited on a chip containing prefabricated Au microelectrodes, and then the chip was dried in vacuum. Electron beam lithography (EBL) was employed to define an inner electrode pattern that connected the nanorods with the microelectrodes. A resist layer of polymethyl methacrylate (PMMA) was prepared by the following procedure: 950 PMMA C3 was spin-coated at about 500 rpm (about 10 s) and about 3000 rpm (45 s) followed by

baking at about 180 °C for about 4 mins. EBL was carried out using a SEM (JEOL JSM-6360 SEM, Tokyo, Japan), equipped with the Raith SEM lithography kits (Raith ELPHY Quantum, Dortmund, Germany) at 30 kV acceleration voltage and 40 pA beam current. Cr (10nm) and Au (400 nm) were then thermally evaporated onto the e-beam resist-coated substrate after it had been developed with 1:3 (v/v) methyl isobutyl ketone/isopropyl alcohol (MIBK/IPA) solution for about 30 mins, and then rinsed with IPA. Finally, the two ends of one nanorod were connected with the microelectrode.

[0063] Assembly of ferritin into the nanogap

[0064] After the nanorods with OWL-fabricated nanogaps were successfully connected to microelectrodes by e-beam lithography, they were oxygen plasma cleaned for about 1 min to remove organic contamination on the wafer surface, followed by cleaning in ethanol and drying with N₂. The wafer was then immersed in a solution of 1 mM mercaptopropionic acid (MPA) for about 2 hours and rinsed thrice with water. Then, it was immersed in a 0.1 M phosphate buffered saline (PBS) buffer of 2.5 mg ferritin and 50 mg/l 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) overnight. Finally, the nanogap electrode was removed from the solution and rinsed with PBS and water, and then blown dry with N₂.

[0065] Electrical Measurements

[0066] The current-voltage characteristics of the devices were obtained using a closed cycle cryogenic wafer probe station (Lakeshore CRX-4K, Westerville, OH, USA) for connection the microelectrodes, combined with semiconductor parameter analyzer (Keithley 4200-SCS, Cleveland, OH, USA) for application of potential and measurement of current. In typical experiments, the measurements were conducted under vacuum (5×10^{-5} torr).

Characterization of ferritin-based ~12nm nanogap device

[0067] 360 nm diameter wire structures with ~12 nm nanogaps 400, according to the size of ferritin, were employed to fabricate protein-based device 402 on a substrate 404 with

gold microelectrodes 406, that can be arranged to couple to a bias voltage 408. Two sides of 12 nm gaps 400 were first covalently modified with 3-Mercaptopropionic acid (MPA) via Au-S bond and then two ends of each gold wire 410 were connected to the electrodes 406 by e-beam lithography and subsequent chromium and gold thermal deposition (Figures 4a and 4b). A high quality ferritin monolayer was prepared and ferritin nanodevices based on OWL-generated nanogaps have been fabricated, as is illustrated in Figure 4c. The MPA-modified nanogap device 402 was immersed in a PBS solution (pH 7.4) of 2.5 mg/ml ferritin and 50 mg/ml 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) overnight, rinsed with PBS and water, and then dried with N₂ flow. With the activation of EDC, amide bonds were formed between ferritin 412 and MPA, and thereby ferritin molecules 412 were covalently assembled within nanogaps 400, which ensured a strong coupling between protein 412 and electrodes 406 (Figure 4d).

Electrical properties of ferritin-based nanogap device

[0068] Electrical measurements were conducted under a vacuum of 5×10^{-5} Torr at room temperature. Two terminal current-voltage (*I-V*) characteristics of such ~12 nm gap devices were obtained before and after ferritin assembly, as shown in Figure 5. There is no conductivity of the blank nanogap 500 that can be observed within the noise limit of the measurement (<10 pA). However, the nanogap devices with ferritin 502, 504, 506, 508, 510 inside show an *I-V* response, which demonstrate the immobilization of the protein molecules across the nanogap via covalently bonding to each of gold electrodes on opposite sides of the gap. This shows the characteristics and presence of a protein-based transport junction.

[0069]. The *I-V* curves of such ferritin nanodevice exhibit a reversibly programmable resistance switching as follows. When the potential is applied higher than ~ +0.7 V (V_{set}), current abruptly increase, reflecting a change of the device from high resistance (OFF state) to low resistance (ON state). Then, the device keeps stable in this high conductivity state until the potential falls to around -0.8 V (V_{reset}). Once voltage is lower than V_{reset} , the current decreases immediately and the ON state is accordingly changed back to OFF state with the low conductivity. Such cyclic switches can last for several times or rounds

of scanning and maintain stable bi-state of conductivity. In addition, for different ferritin devices, the magnitude of current measured may be different, the range of which is from about 800 nA to about 1 mA under about +1 V bias, as seen in Figures 6a to 6d, and the values of V_{set} and V_{reset} also change correspondingly. This difference is presumably ascribed to the number of ferritin molecules that actually span the nanogap and chemically connect with the each gap-side, since the roughness and morphology of the gold electrode surface should be varying.

[0070] From the hysteretic I - V behavior observed in the ferritin monolayer assembled within nanogap, the two-terminal electrical device can be attributed to the category of memristor and can be employed for nonvolatile memory. An important characteristic of memristor, that is the ability of reading, writing, and erasing of data has been investigated.

[0071] Figure 7 shows the write-read-erase cycle of a ferritin-based nanogap device. A continuous and various biases 700 were applied to control the state of the device. +1 V for writing (higher than V_{set}) was used to set the device to the ON state while -1 V for erasing (lower than V_{reset}) was used to reset it back to OFF state. Additionally, +0.6 V, which is between V_{set} and V_{reset} , is employed to read the current values 702 in such two states of device. It is observed that the currents of device in ON state are much higher than the ones in OFF state, despite having all of them being recorded with the same reading bias, +0.6 V. Significantly, the programmable switching is shown to be cyclically operated many times as seen in Figure 7 and a steady ON/OFF ratio is shown to be maintained.

Electrical properties of nanogap device assembled with reconstituted ferritin (Apo-ferritin and Iron ion)

[0072] Ferritin is not only the main intracellular iron storage protein, but also a notable redox protein. The active center of ferritin, a stable ferric-oxyhydroxy-phosphate complex core, is the key factor of electron transfer within electrochemical devices in solution. Therefore, such redox center have a direct relationship with the ferritin-based transport junction in solid state. In order to explore the mechanism of the electron

transport in this ferritin-based memristor, the role of this iron complex center was studied by measuring conductivity of apoferritin assembled within nanogap devices as that described hereinabove.

[0073] Figure 8a shows the I - V characteristics of the apoferritin-based device about 12 nm OWL-generated gaps before 800 and after reconstitution of iron core (802, 804, 806, 808, 810; scan for 5 five times under vacuum) inside apoferritin shells. Figure 8b shows I - V curves of OWL-generated nanogaps before 812 and after 814 assembly of apoferritin.

[0074] The magnitude of current of the apoferritin-based device is several orders of magnitude lower than that of the ferritin-based device. At the same time, the switching changes of resistance also disappear. After reconstitute the iron-core active center was reconstituted in apoferritin according the method described in Harrison, P. M.; Fischbach, F. A.; Hoy, T. G.; Haggis, G. H. *Nature* 1967, 216, pp. 188-1190 for about 24 hours, the significant current transport and the hysteretic I - V results can be detected again (Figure 8b). These results demonstrate that the iron complex core of ferritin also participates the electron transfer in the solid-state devices and plays crucial role in the memristive behavior of ferritin as an electronic material.

[0075] Since ferric-oxyhydroxy-phosphate complex core in ferritin undertake the functions to accomplish electron transfer and perform the memory phenomenon for the nanodevice, the following mechanism is proposed based on the structure of such ferric core. In one molecule of ferritin, Fe (III) is deposited as a hydrous ferric oxide core containing several thousand atom of iron (less than 4500). However, there are several hundred molecular of inorganic phosphate can also be accommodated throughout the core, which cause ferritin iron core to form some disordered regions. Thus, the active center of ferritin can be regarded as natural doped ferric oxides that can ensure the efficient electron transport through ferritin molecule. Moreover, after applied bias to the ferritin device, the valent state of iron may be reduced from ferric to ferrous. As monoatomic Fe (II) has more freedom than Fe (III) and can flow more easily, which is also the mechanism of iron release in vivo, the conductivity of ferritin molecule should abruptly increase, once more monoatomic Fe (II) has been formed with the help of electric field. In solid-state transport nanojunctions such as the embodiment described above, the reduction/oxidation of the molecule and the neutralization of the

reduced/oxidized molecule are both attributed to current flow, but neutralization is a slower process as compared to the redox reaction. Thus, this can explain the hysteretic I - V characteristics of ferritin-based nanogap device.

[0076] By contrast, the measurements of the same devices as mentioned before were carried out in air and the supporting information in Figures 9 and 10 reveals that the controllable resistive switching is affected causing the V_{set} to be enhanced and lower ON/OFF ratio. These observations supports the proposed mechanism described above, since oxygen can retard the reduction from Fe (III) to Fe (II). Besides, temperature dependent I - V characteristics of the ferritin-fabricated device as in Figure 11 provide further evidence in support of such explanation, that the hysteretic behavior of I - V curves 1100, 1102, 1104, 1106 perform more distinctly, that is as reflected by the increasing hysteresis, coupling with increasing temperature of 300K (1100), 240K (1102), 140K (1104), 60K (1106), since under cryogenic condition the freedom of monoatomic iron is very limited no matter ferric or ferrous.

[0077] A single-rod memristor nanodevice that combines ferritin as electronic material with OWL-generated nanogap in accordance to various embodiment is developed for first time. There is convincing evidence to demonstrate that proteins, especially the redox proteins, can achieve efficient transport junctions in solid-state electronic devices. At the same time, the approach allows easy investigation on the electric properties of redox proteins, and thereby creating a new testbed to clarify the mechanism of electron transport in proteins. Moreover, since such ferritin-based nanodevice have the characteristics of memristor, it can also provide a new platform for the exploration of memristive nanodevices, which introduce natural biomaterials for applications to electronics and physics.

[0078] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A memristor comprising:
 - two electrically conducting terminals arranged with a nanometer-scaled gap therebetween; and
 - a protein disposed in the gap to form a protein-based transport junction between the two electrically conducting terminals,
 - wherein the protein is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a change in bias voltage applied across the two electrically conducting terminals; and wherein the protein comprises a redox protein.
2. The memristor as claimed in claim 1, wherein the protein comprises a protein having a metal oxide core.
3. The memristor as claimed in claim 1 or 2, wherein the protein is selected from the group consisting of ferritin, transferrin, lactoferrin, and a mixture thereof.
4. The memristor as claimed in any one of claims 1 to 3,
 - wherein the protein-based transport junction is configured to switch from the high resistance state to the low resistance state by applying a first predetermined bias voltage across the two electrically conducting terminals.
5. The memristor as claimed in claim 4, wherein the first predetermined bias voltage is about +0.7 V to about +3 V.
6. The memristor as claimed in claim 5, wherein the first predetermined bias voltage is about +0.7 V.
7. The memristor as claimed in any one of claims 1 to 3,

wherein the protein-based transport junction is configured to switch from the low resistance state to the high resistance state by applying a second predetermined bias voltage across the two electrically conducting terminals.

8. The memristor as claimed in claim 7, wherein the second predetermined bias voltage is about -0.8 V to about -3 V.

9. The memristor as claimed in claim 8, wherein the second predetermined bias voltage is about -0.8 V.

10. The memristor as claimed in any one of claims 4 to 9, wherein the memristor is configured to exhibit a resistance hysteresis at bias voltages lower than -0.8V or higher than +0.7V when applied across the two electrically conducting terminals.

11. The memristor as claimed in any one of claims 1 to 10, wherein the memristor expresses a non-volatile resistance change.

12. The memristor as claimed in any one of claims 1 to 11, wherein the memristor is configured to perform a reading operation by applying a reading voltage across the two electrically conducting terminals and obtaining a current value in the high resistance state or in the low resistance state.

13. The memristor as claimed in claim 12, wherein the reading voltage is about +0.6 V to about -0.7 V.

14. The memristor as claimed in claim 13, wherein the reading voltage is about +0.6 V.

15. The memristor as claimed in any one of claims 1 to 14, further comprising a substrate, on which the two electrically conducting terminals are disposed.

16. The memristor as claimed in claim 15, wherein the substrate is made of Si or Si/SiO₂.

17. The memristor as claimed in any one of claims 1 to 16, wherein each of the two electrically conducting terminals is made of a material selected from the group consisting of gold (Au), chromium (Cr), platinum (Pt), titanium (Ti), palladium (Pd), silver (Ag), copper (Cu), aluminum (Al), tungsten (W) and an alloy thereof.

18. The memristor as claimed in claim 17, wherein the two electrically conducting terminals are made of the same material.

19. The memristor as claimed in claim 17, wherein the two electrically conducting terminals are made of different materials.

20. The memristor as claimed in any one of claims 1 to 19, wherein the gap has a width of about 2 nm to about 100 nm.

21. The memristor as claimed in claim 20, wherein the gap has a width of about 12 nm.

22. A method of fabricating a memristor, the method comprising:
preparing a nanometer-scaled gap between two electrically conducting terminals;
and

disposing a protein in the gap to form a protein-based transport junction between the two electrically conducting terminals,

wherein the protein is reversibly switchable between two electronic states such that the protein-based transport junction is configured to switch between a high resistance state and a low resistance state in response to a change in bias voltage applied across the two electrically conducting terminals; and wherein the protein comprises a redox protein.

23. The method as claimed in claim 22, wherein the protein is selected from the group consisting of ferritin, transferrin, lactoferrin, and a mixture thereof.

24. The method as claimed in claim 22 or 23, wherein preparing the nanometer-scaled gap between the two electrically conducting terminals comprises:

synthesizing a multisegment nanostructure comprising a nanometer-scaled sacrificial layer formed between electrically conducting materials for the terminals; and

removing the sacrificial layer from the multisegment nanostructure; thereby forming the nanometer-scaled gap between the two electrically conducting terminals.

25. The method as claimed in claim 24, wherein synthesizing the multisegment nanostructure comprises electrochemically depositing the electrically conducting materials and the sacrificial layer therebetween in a membrane template.

26. The method as claimed in claim 25, wherein the membrane template comprises an anodized aluminumoxide (AAO) membrane template.

27. The method as claimed in claim 25 or 26, whether the membrane template has an average pore size of about 360 nm.

28. The method as claimed in any one of claims 24 to 27, wherein the nanostructure comprises a nanorod.

29. The method as claimed in any one of claims 24 to 28, wherein the electrically conducting materials are selected from the group consisting of gold (Au), chromium (Cr), platinum (Pt), titanium (Ti), palladium (Pd), silver (Ag), copper (Cu), aluminum (Al), tungsten (W) and an alloy thereof.

30. The method as claimed in any one of claims 24 to 29, wherein removing the sacrificial layer is performed by etching means.

31. The method as claimed in any one of claims 24 to 30, wherein the sacrificial layer is made of nickel.

32. The method as claimed in any one of claims 22 to 31, wherein disposing the protein in the gap comprises

mixing the two electrically conducting terminals arranged with the nanometer scaled gap therebetween with a buffer of protein and a crosslinking agent for about 6 hours to about 20 hours.

33. The method as claimed in claim 32, wherein the crosslinking agent is selected from the group consisting of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC), *N,N*-dicyclohexylcarbodiimide, *N,N*-diisopropylcarbodiimide, and a derivative thereof.

34. The method as claimed in any one of claims 24 to 33, further comprising coupling the nanostructure to a microelectrode, prior to disposing the protein in the gap.

35. The method as claimed in claim 34, wherein the nanostructure is coupled to the microelectrode by e-beam lithography and subsequent chromium and gold thermal deposition.

36. The method as claimed in claim 34 or 35, wherein the microelectrode is obtained by thermally evaporating chromium and gold onto a resist-patterned wafer, followed by incubating the wafer and subsequently by removing the resist from the wafer.

37. The method as claimed in any one of claims 22 to 36, where in the gap is covalently modified with 3-mercaptopropionic acid (MPA).