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(54) **NANOSTRUCTURED ELECTRODE FOR ENERGY STORAGE DEVICE**

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**Related U.S. Application Data**

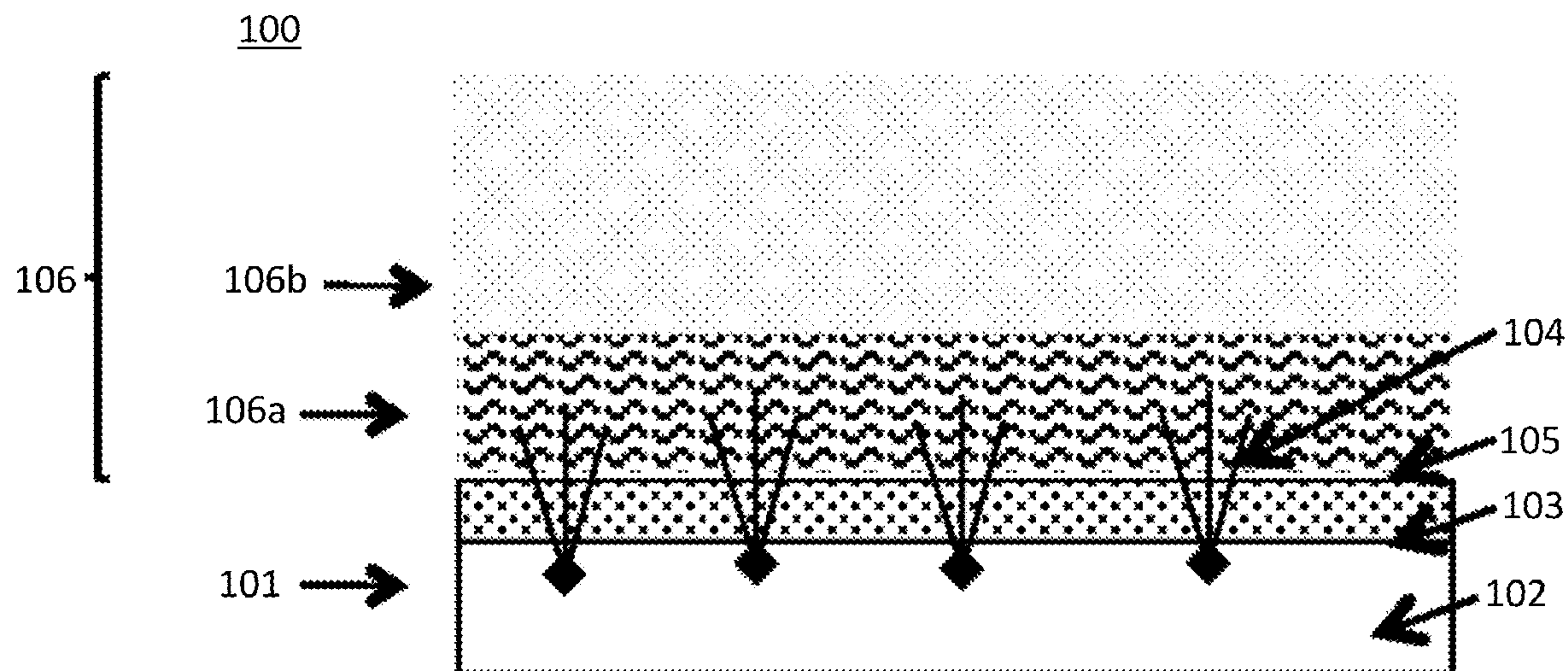
(63) Continuation of application No. PCT/US2015/  
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(60) Provisional application No. 62/061,947, filed on Oct.  
9, 2014.

(57)

**ABSTRACT**

An electrode for use in energy storage devices is disclosed.  
The electrode includes carbide non-whiskers.



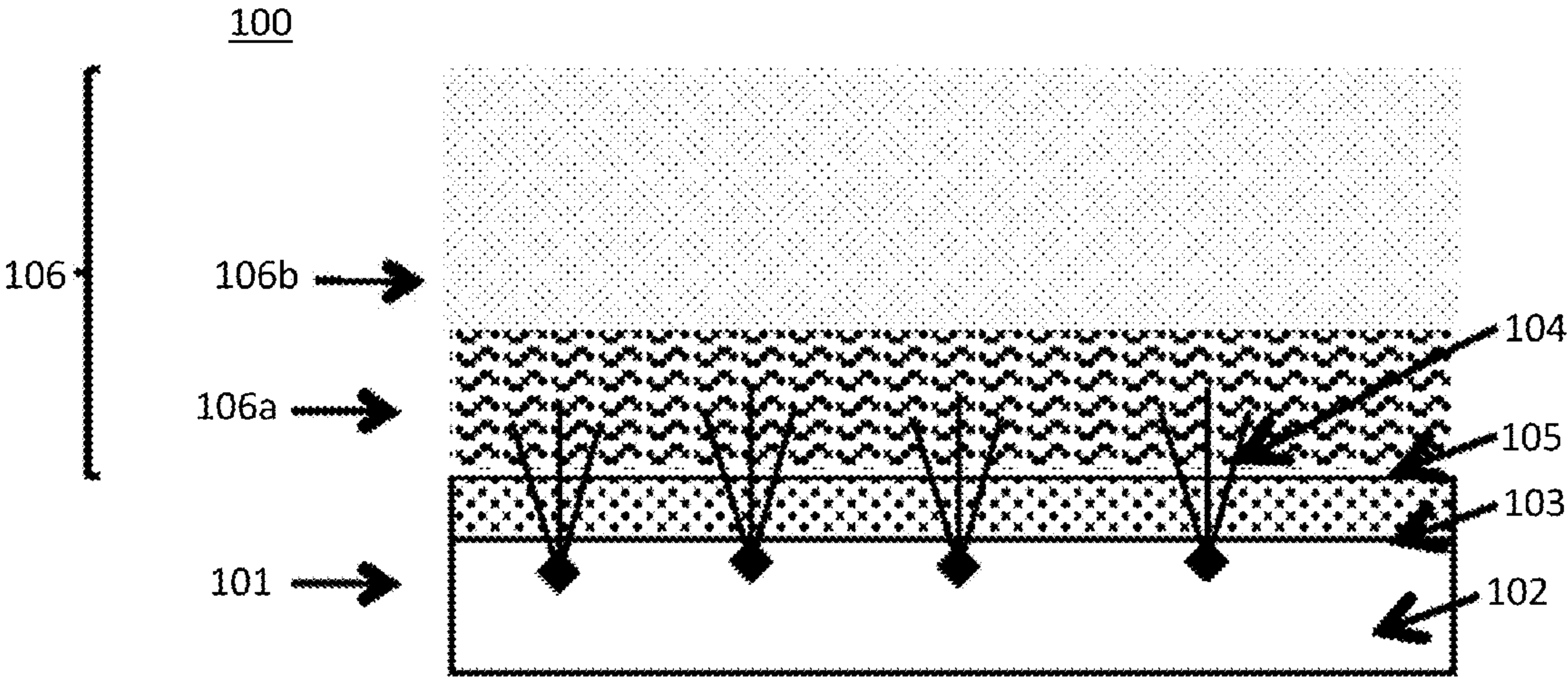
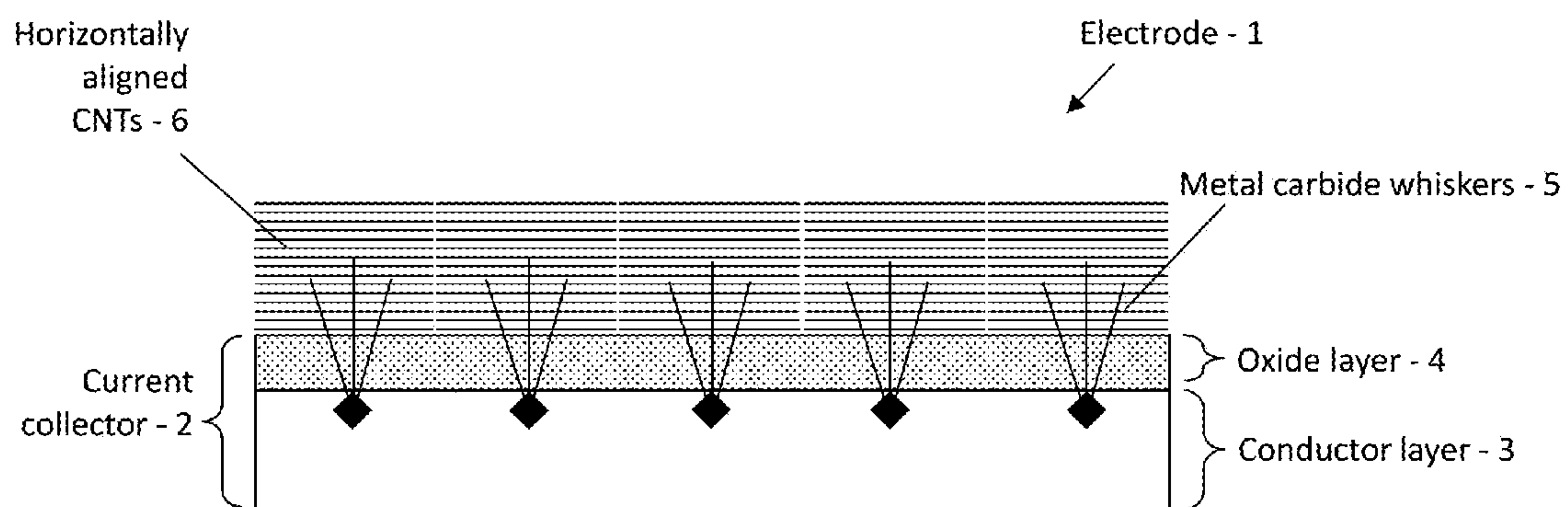
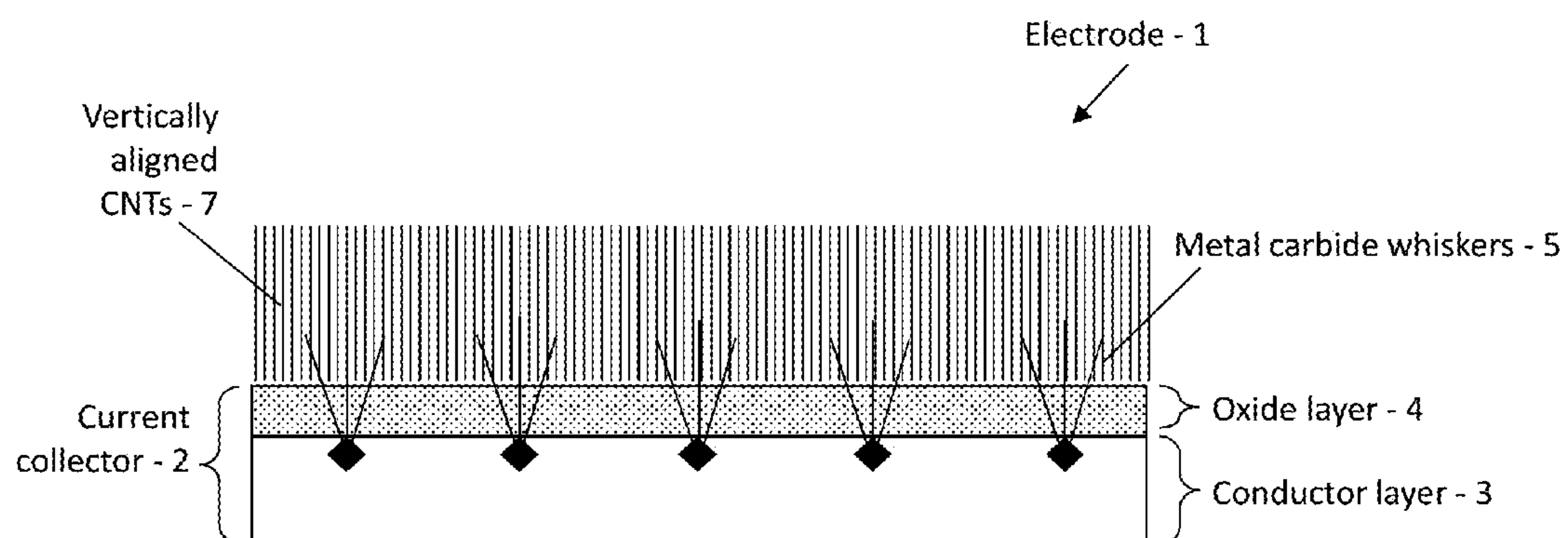


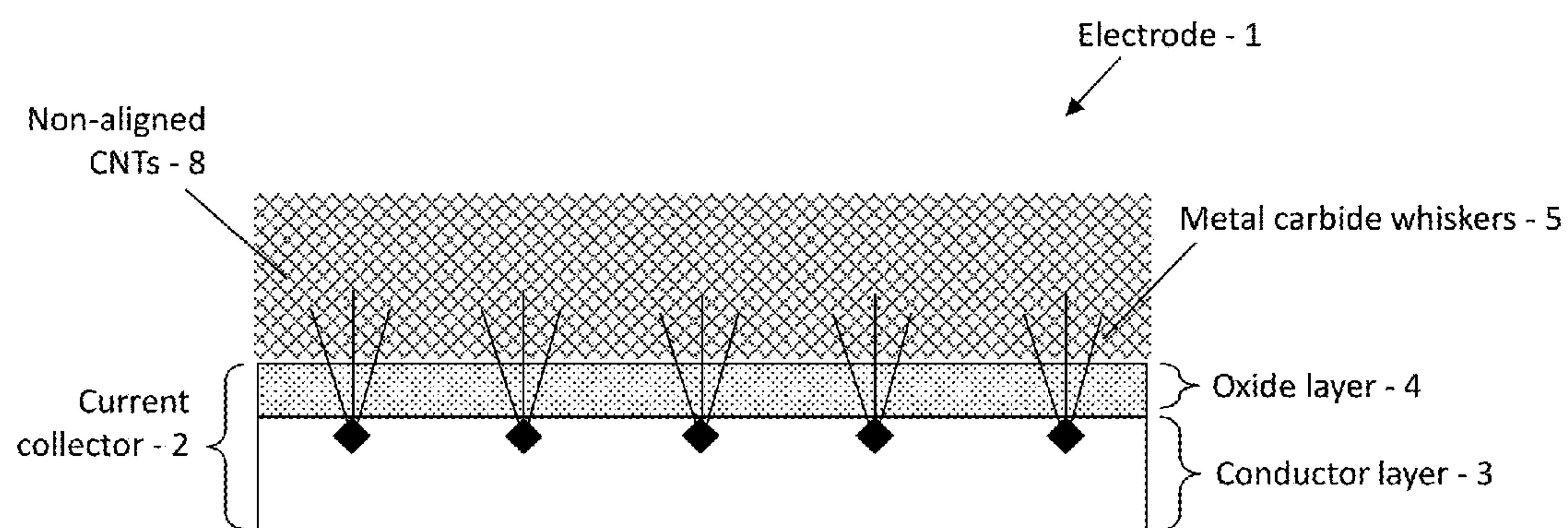
FIG. 1



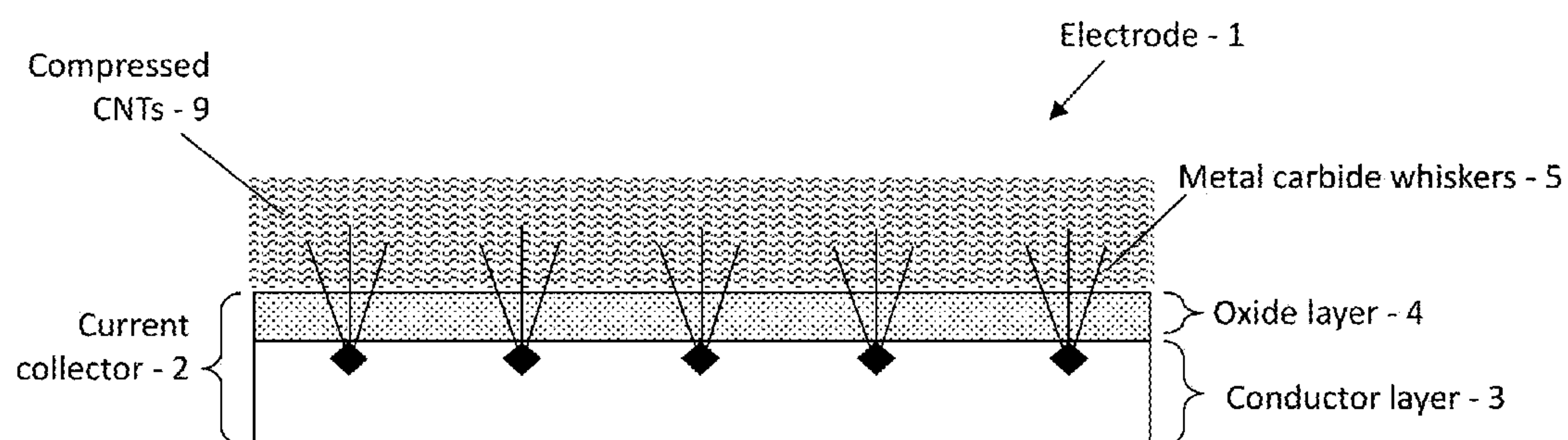
**FIG. 2A**



**FIG. 2B**

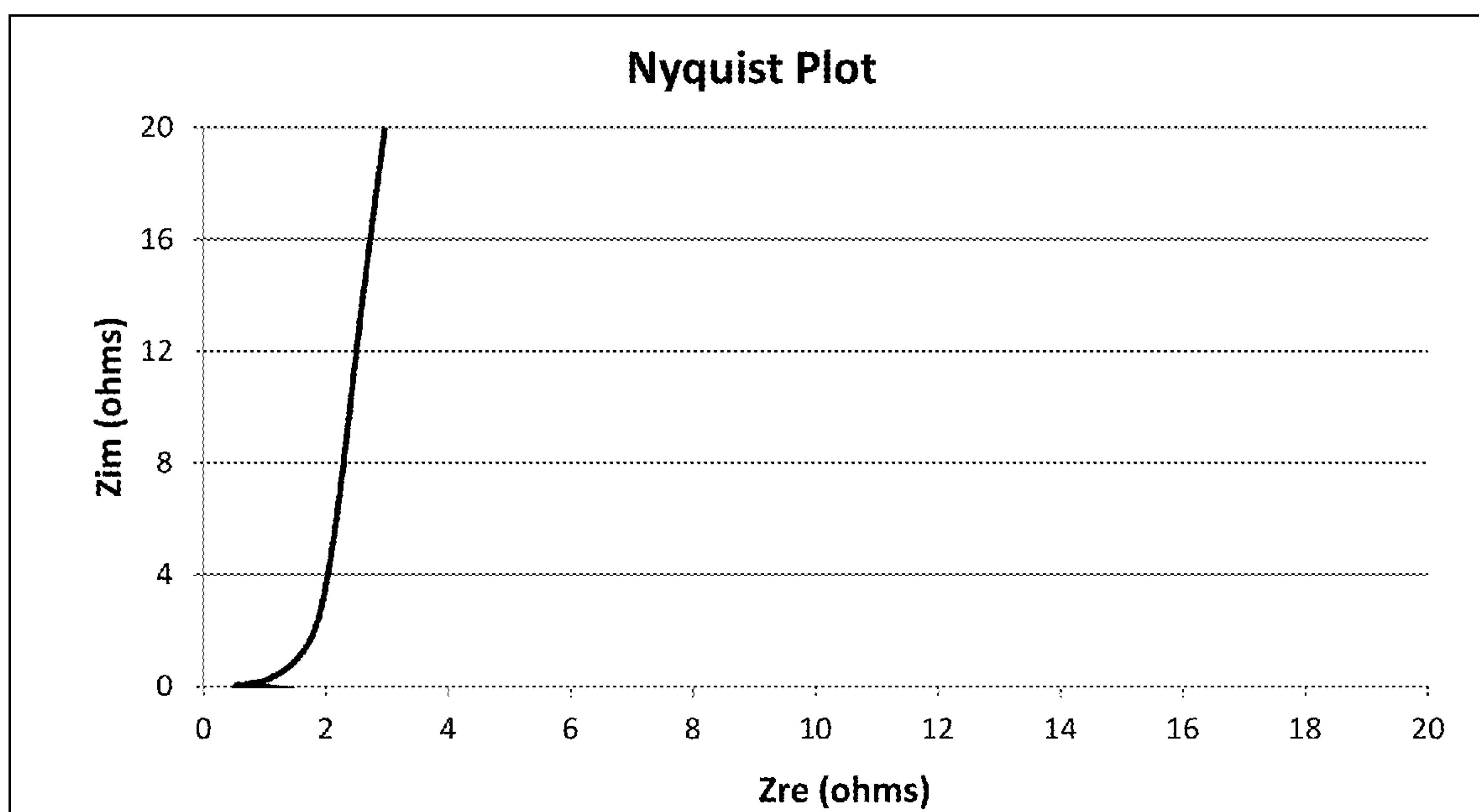


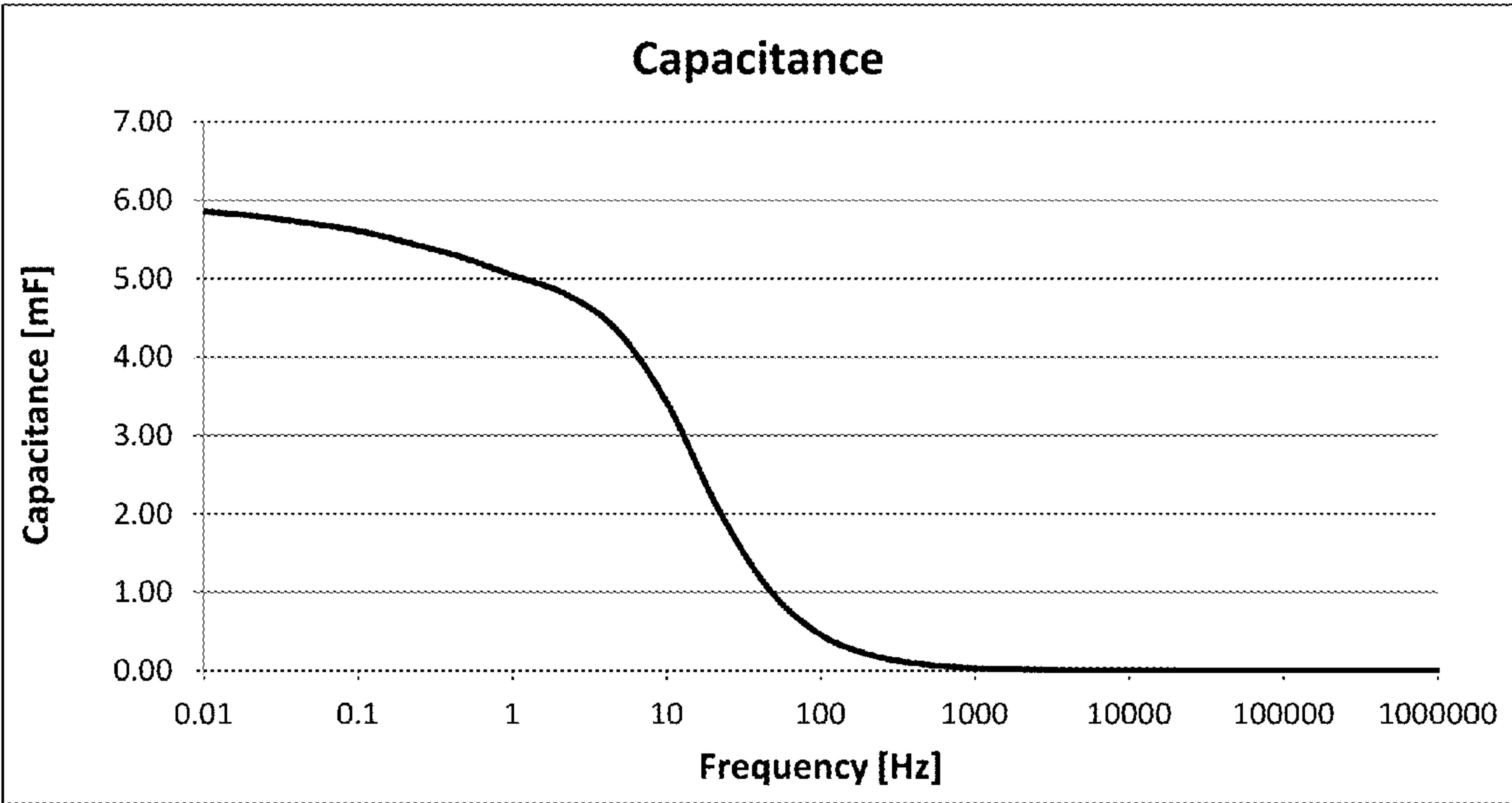
**FIG. 2C**



**FIG. 2D**

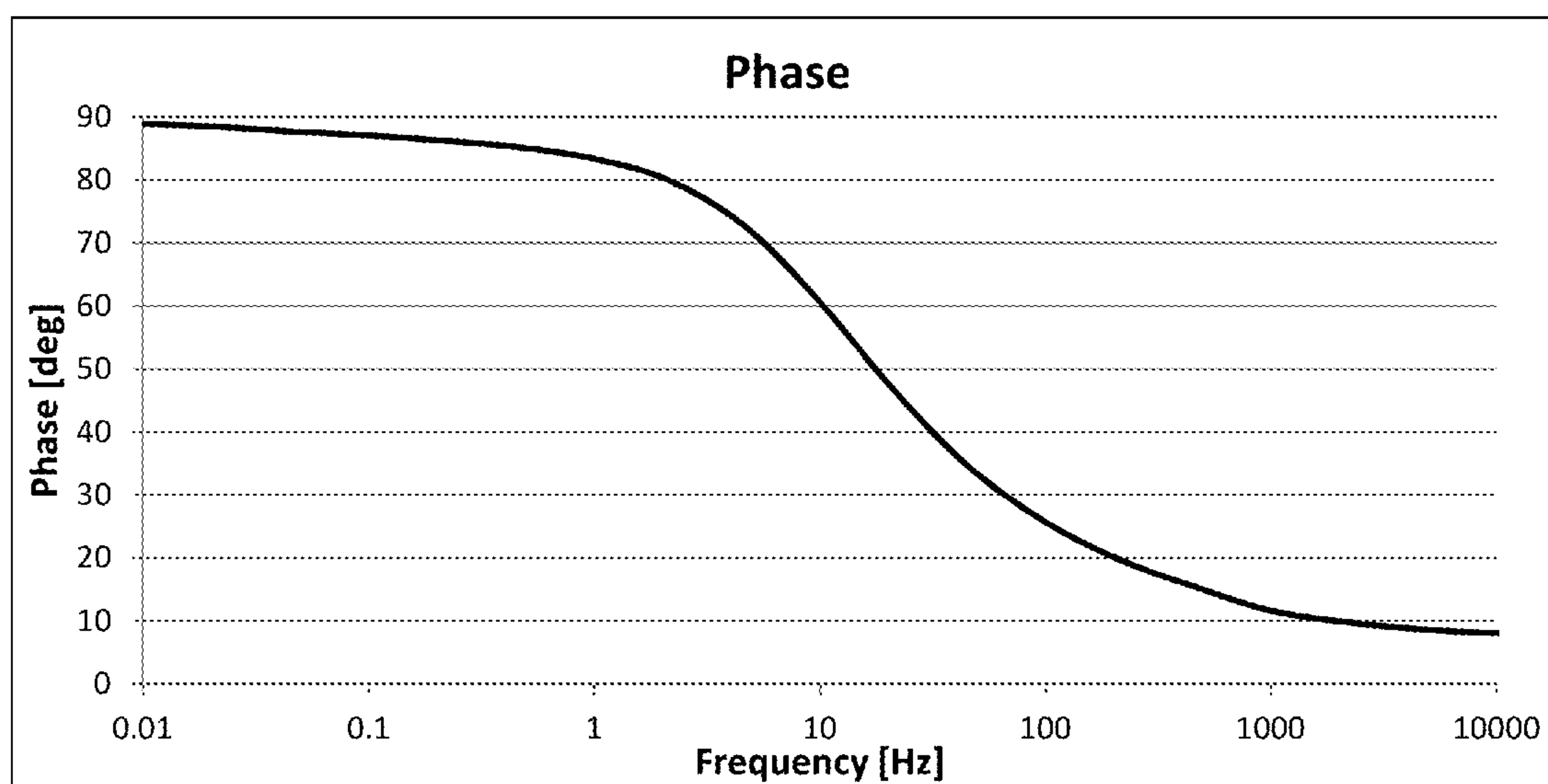


**FIG. 3**



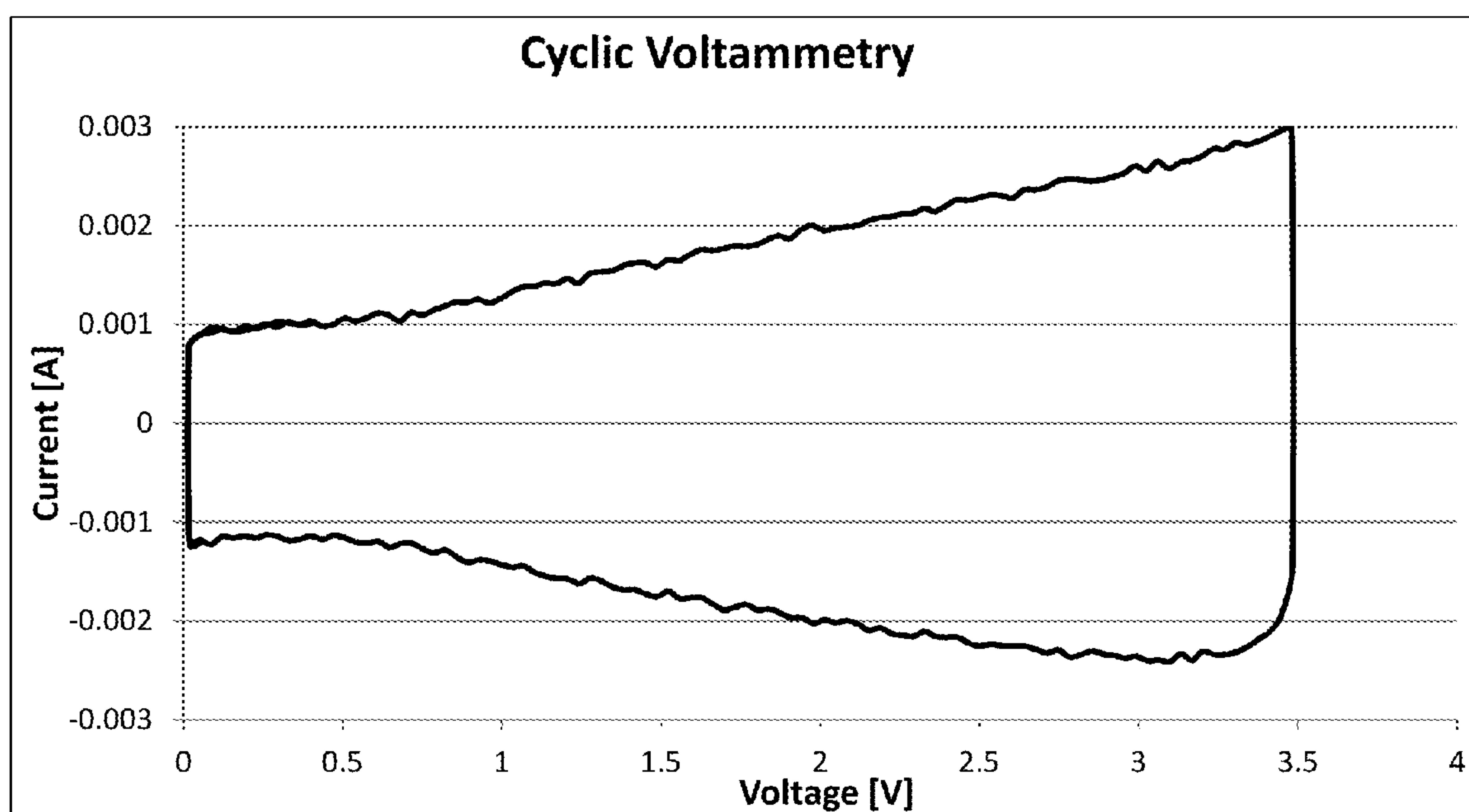
Capacitance of 1 layer of CNTs on Al<sub>4</sub>C<sub>3</sub> on 50 μm aluminum foil.

*FIG. 4A*



Phase of 1 layer of CNTs on  $\text{Al}_4\text{C}_3$  on 50  $\mu\text{m}$  aluminum foil.

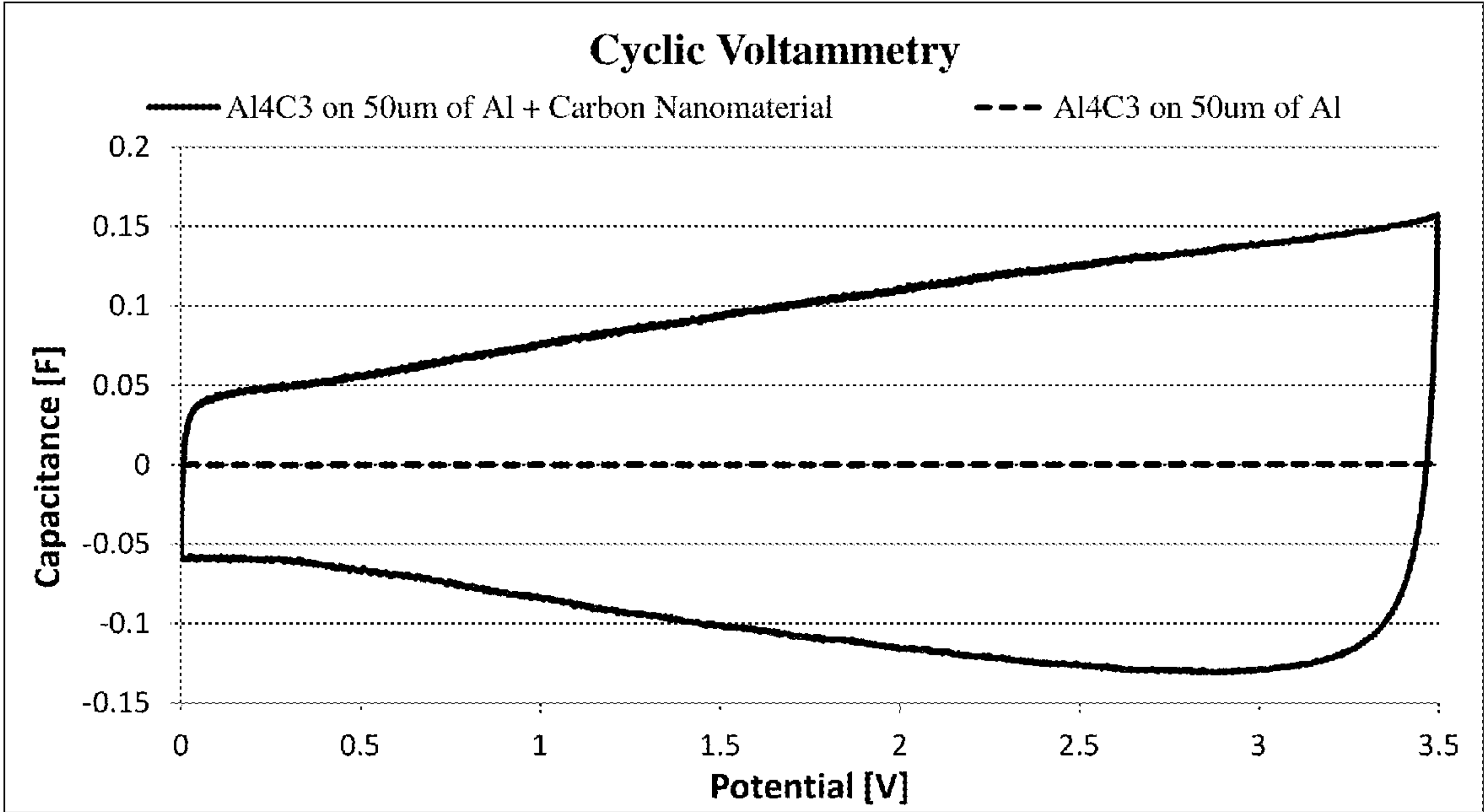
**FIG. 4B**



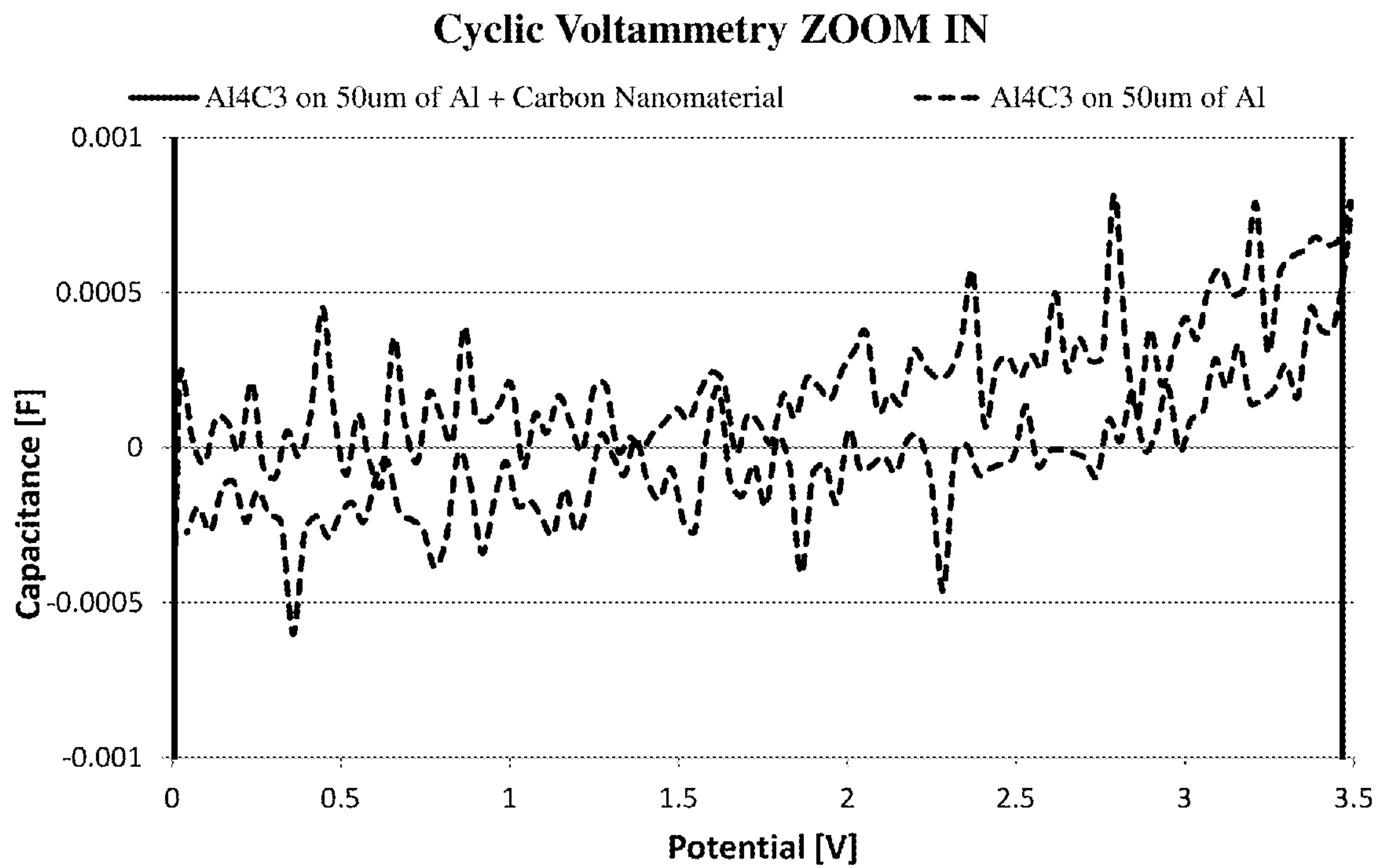
Cyclic voltammetry of 1 layer of CNTs on  $\text{Al}_4\text{C}_3$  on 50  $\mu\text{m}$  aluminum foil.

**FIG. 4C**

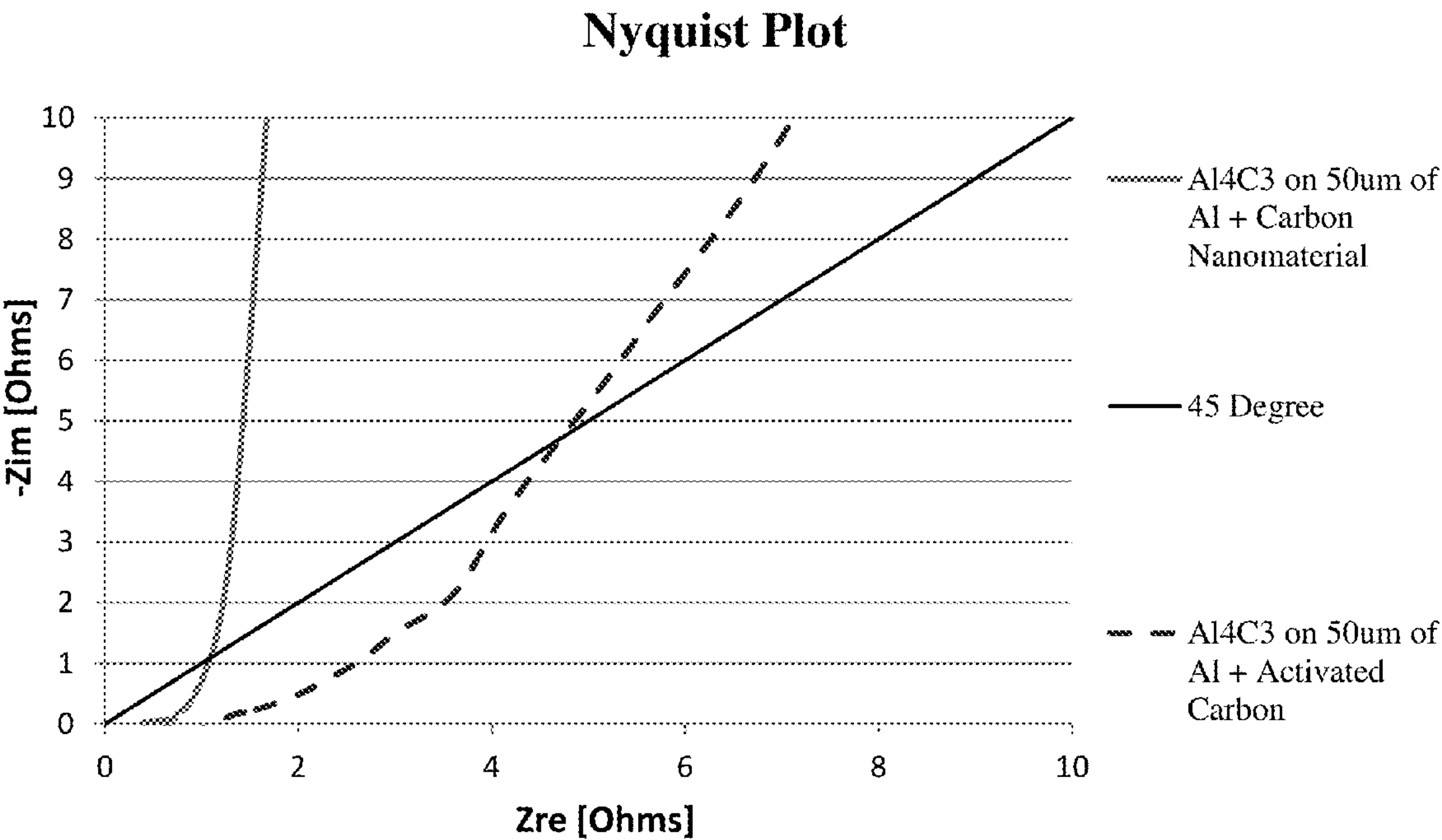




*FIG. 5A*



**FIG. 5B**



**FIG. 5C**

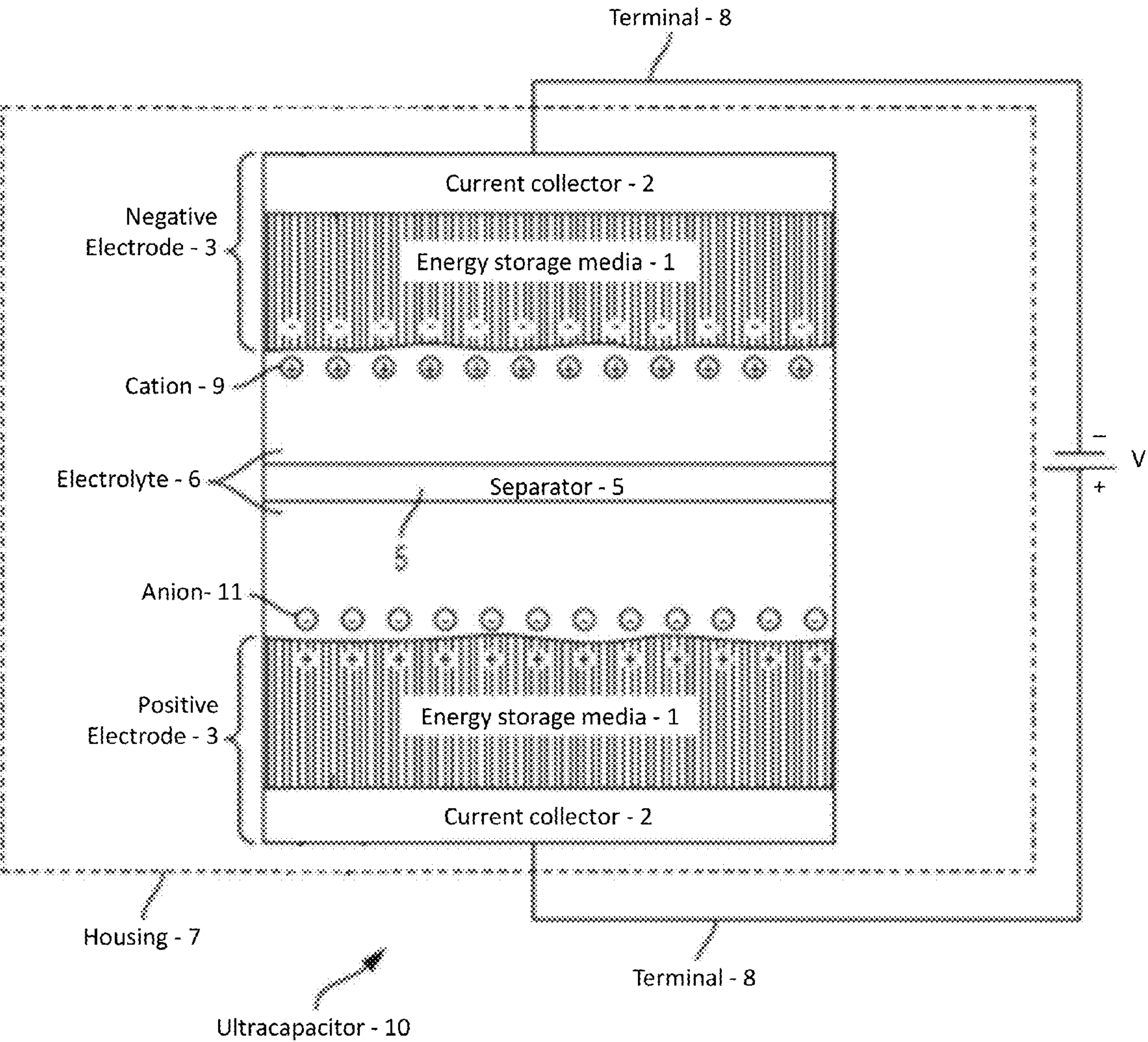


FIG. 6



## NANOSTRUCTURED ELECTRODE FOR ENERGY STORAGE DEVICE

### CROSS REFERENCE TO RELATED APPLICATIONS

**[0001]** The present application is a continuation of International Patent Application No. PCT/US2015/055032, filed Oct. 9, 2015, and entitled “NANOSTRUCTURED ELECTRODE FOR ENERGY STORAGE DEVICE,” which claims priority to U.S. Provisional Application 62/061,947 filed Oct. 9, 2014 and entitled ELECTRODE FOR ENERGY STORAGE DEVICE USING ANODIZED ALUMINUM, the entire contents of which are incorporated herein by reference.

### STATEMENT OF FEDERALLY SPONSORED RESEARCH

**[0002]** This invention was made with government support under grant DE-AR0000035/0001 awarded by the United States Department of Energy (ARPA-E) and/or DE-DE-EE0005503/001 awarded by the United States Department of Energy (EERE). The United States government has certain rights in the invention.

### TECHNICAL FIELD

**[0003]** The present invention relates to producing electrodes comprising carbon nanotube aggregates for use in energy storage devices, including methods for producing such electrodes and energy storage devices that utilize such electrodes.

### BACKGROUND

**[0004]** Carbon nanotubes (CNTs) are carbon structures that exhibit a variety of properties. Many of the properties suggest opportunities for improvements in a variety of technology areas. These technology areas include electronic device materials, optical materials as well as conducting and other materials. For example, CNTs are proving to be useful for energy storage in capacitors.

**[0005]** However, effective transfer of the CNTs onto a current collector for a capacitor has proven to be challenging. Further, techniques have not enabled transfer of CNTs in a form that will provide for desired performance capabilities, e.g., power density, energy density, maximum voltage rating, equivalent series resistance (ESR), frequency response, cycle efficiency, and stability. For example, a bonding layer is typically used to cause CNTs to adhere to the surface of a current collector. The bonding layer typically affects the performance of the resulting capacitor in a number of ways, including increasing the ESR and decreasing the energy density and power density.

**[0006]** Thus, what are needed are methods and apparatus for production of a high performance electrode based on carbon nanotubes. Preferably, the methods and apparatus are simple to perform and thus offer reduced cost of manufacture, as well as an improved rate of production.

### BRIEF SUMMARY OF CERTAIN EMBODIMENTS

**[0007]** In one embodiment, an electrode is provided. The electrode includes a current collector comprising aluminum with an aluminum carbide layer on at least one surface, on

which at least one layer of CNTs is disposed. The electrode may comprise vertically-aligned, horizontally-aligned, or nonaligned (e.g., tangled or clustered) CNTs. The electrode may comprise compressed CNTs. The electrode may comprise single-walled, double-walled, or multiwalled CNTs. The electrode may comprise multiple layers of CNTs.

**[0008]** In another embodiment, a method for fabricating an electrode is provided. The method comprises selecting a current collector with a layer of aluminum carbide on at least one surface of the current collector and disposing CNTs onto the aluminum carbide layer. Disposing CNTs onto the aluminum carbide layer may comprise disposing vertically-aligned, horizontally-aligned, or nonaligned (e.g., tangled or clustered) CNTs. The resulting electrode may comprise vertically-aligned, horizontally-aligned, or nonaligned (e.g., tangled or clustered) CNTs. Disposing CNTs onto the aluminum carbide layer may comprise disposing compressed CNTs and/or compressing the CNTs after they have been disposed on the aluminum carbide layer. The resulting electrode may comprise compressed CNTs. Disposing CNTs onto the aluminum carbide layer may comprise disposing single-walled, double-walled, or multiwalled CNTs. The resulting electrode may comprise single-walled, double-walled, or multiwalled CNTs. The method may further comprise disposing additional layers of CNTs onto the layer of CNT disposed onto the aluminum carbide layer, which additional layers of CNTs may be vertically-aligned, horizontally-aligned, or nonaligned (e.g., tangled or clustered) CNTs; compressed CNTs; or single-walled, double-walled, or multiwalled CNTs.

**[0009]** Disposing CNTs onto the aluminum carbide layer may comprise any variety of methods for creating a layer of CNTs on a surface, including transferring CNTs from a solution, transferring CNTs using any variety of dry transfer methods, growing CNTs directly on the aluminum carbide layer, and any combination of these methods. In certain embodiments, a layer of CNTs is grown directly on an aluminum current collector having an aluminum carbide layer on at least one surface. The layer may comprise single-walled, double-walled, or multiwalled CNTs. In certain embodiments, a layer of CNTs is transferred to the current collector using any variety of dry transfer methods, such as transfer tape, compression. In certain embodiments, a dry transfer method is used to add additional layers of CNTs onto a layer of CNTs that has been disposed onto an aluminum carbide layer of the current collector. In certain embodiments, a layer of CNTs is transferred to the current collector using any variety of wet, solvent-based transfer methods, including precipitation, evaporation, spray-drying,

**[0010]** In a further embodiment, an ultracapacitor is provided. The ultracapacitor includes at least one electrode of the type described herein.

**[0011]** The ultracapacitor may further comprise an electrolyte with certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or separator. In certain embodiments, the electrolyte is a solution comprising at least one inorganic or organic salt, such as an ionic liquid, and optionally further comprising at least one solvent. In certain embodiments, the electrolyte is a gel comprising at least one ionic liquid and at least one gelling agent, and optionally comprising other additives such as solvents, salts, and surfactants. In certain embodiments, the electrolyte is a solid polymer electrolyte comprising at least one



inorganic or organic salt, such as an ionic liquid, and at least one polymeric material, such as a fluoropolymer (e.g., polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK), polyvinylidene difluoride (PVDF), or co-polymers thereof) and optionally comprising other additives such as solvents, salts, and surfactants. In a particular embodiment, the electrolyte is substantially free of moisture and other contaminants that may adversely affect the performance of the ultracapacitor.

**[0012]** The ultracapacitor may further comprise a separator to provide electrical separation between a positive electrode and a negative electrode of the ultracapacitor, which separator has certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or electrolyte. In certain embodiments, the separator comprises a material selected from the group consisting of polyamide, PTFE, PEEK, PVDF, aluminum oxide ( $\text{Al}_2\text{O}_3$ ), fiberglass, fiberglass reinforced plastic, or any combination thereof. In a particular embodiment, the separator is substantially free of moisture. In another particular embodiment, the separator is substantially hydrophobic.

**[0013]** In yet another embodiment, a method for fabricating an ultracapacitor is provided. The method includes selecting an electrode, which comprises a current collector with an aluminum carbide layer on at least one surface and CNTs disposed on the aluminum carbide layer, and including the electrode in an ultracapacitor. The method may further comprise selecting an electrolyte with certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or separator. The method may further comprise selecting a separator with certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or electrolyte.

#### BRIEF DESCRIPTION OF DRAWINGS

**[0014]** The foregoing and other features and advantages of the disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

**[0015]** FIG. 1 is a block diagrams depicting an embodiment of an electrode of the present disclosure;

**[0016]** FIGS. 2A-2D are block diagrams depicting embodiments of electrodes of the present disclosure;

**[0017]** FIG. 3 is a Nyquist plot for an ultracapacitor of the present disclosure;

**[0018]** FIG. 4A is a capacitance versus frequency plot for an ultracapacitor of the present disclosure;

**[0019]** FIG. 4B is a phase versus frequency plot for an ultracapacitor of the present disclosure;

**[0020]** FIG. 4C is a cyclic voltammetry plot for;

**[0021]** FIG. 5A is a cyclic voltammetry plot for an ultracapacitor of the present disclosure with and without carbon nanotubes;

**[0022]** FIG. 5B is a detailed view of a portion of the plot of FIG. 5B;

**[0023]** FIG. 5C is a Nyquist plot for an ultracapacitor of the present disclosure with and without carbon nanotubes; and

**[0024]** FIG. 6 is a block diagrams depicting an embodiment of an ultracapacitor of the present disclosure.

#### DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

**[0025]** Disclosed are methods and apparatus for providing a high performance electrode for an energy storage device, e.g., an ultracapacitor, where the electrode includes an aluminum current collector with a layer of aluminum carbide on at least one surface and carbon nanotubes (CNTs) disposed on the aluminum carbide layer. Advantageously, the electrode may be fabricated from mass-produced materials, e.g., aluminum carbide coated current collectors and CNTs. Energy storage devices, such as ultracapacitors, that incorporate the presently disclosed electrode exhibit, among other things, higher performance than previously achievable, in terms of at least one of gravimetric power density (power as a function of weight), volumetric power density (power as a function of volume), gravimetric energy density (energy as a function of weight), volumetric energy density (energy as a function of volume), equivalent series resistance (ESR), frequency response, and maximum voltage.

**[0026]** In order to provide some context for the teachings herein, reference is first made to U.S. Pat. No. 7,897,209, entitled “Apparatus and Method for Producing Aligned Carbon Nanotube Aggregate.” This patent is incorporated herein by reference, in its entirety.

**[0027]** The foregoing patent (the “’209 patent”) teaches a process for producing aligned carbon nanotube aggregate.” Accordingly, the teachings of the ’209 patent, which are but one example of techniques for producing aligned carbon nanotube aggregate, may be used to produce carbon nanotube aggregate (CNT) referred to herein.

**[0028]** One example of a device incorporating an electrode as provided herein is provided in U.S. Patent Application Publication No. 2007-0258192, entitled “Engineered Structure for Charge Storage and Method of Making,” also incorporated herein by reference, in its entirety. In general, methods and apparatus disclosed herein may be used to enhance an energy storage system, such as the embodiments disclosed in this publication. One embodiment of such energy storage is referred to as an “ultracapacitor.” However, it should be recognized that the teachings herein may be applicable to other embodiments of energy storage and are therefore not limited to practice with an ultracapacitor.

**[0029]** Electrodes for energy storage devices are disclosed herein. Referring to FIG. 1 in some embodiments, an electrode 100 includes a current collector 101 comprising a conductor layer 102 having at least a first surface 103. The conductor layer may be made of any suitable electrically conductive material, e.g., a metal such as aluminum. In some embodiments, the conductor layer may be rigid (e.g., a metal plate), or flexible (e.g., a metal foil).

**[0030]** In some embodiments, elongated metal carbide nanostructures 104 extend from the first surface 103. The structure of the metal carbide material on the surface 103 of the current collector 101 may vary. The structure of the metal carbide typically material depends on the method by which carbon is deposited on the current collector 101. The structure may depend, among other factors, on the type of metal or metal alloy used as a current collector and the source of carbon used to form the metal carbide layer.

**[0031]** One advantageous metal carbide structure is metal carbide “whiskers,” as shown. These whiskers are thin elongated structures (e.g., nanorods) that extend generally away from the surface 103 of the current collector 101. The whiskers may have a radial thickness of less than 100 nm,



50 nm, 25 nm, 10 nm, or less, e.g., in the range of 1 nm to 100 nm or any subrange thereof. The whiskers may have a longitudinal lengths that is several to many times the radial thickness, e.g., greater than 200 nm, 300 nm, 400 nm, 500 nm, 1  $\mu$ m, 5  $\mu$ m, 10  $\mu$ m, or more, e.g., in the range of 100 nm to 100  $\mu$ m or any subrange thereof.

**[0032]** PCT Publication No. WO WO/2000/044965, dated Aug. 3, 2000 and titled “Manufacture of transition metal carbide and carbonitride whiskers with low amounts of oxygen and residual oxide phases,” the entire disclosure of which is incorporated by reference, discloses transition metal carbide “whiskers” useful in certain embodiments of the present disclosure. Metal carbide whiskers of the present disclosure may comprise any metal, e.g., an alkali metal of Group 1, an alkaline earth metal of Group 2, a transition metal of Groups 3-12, or a post-transition metal of Group 13-15, provided the carbide is relatively stable and demonstrates acceptable electrical performance under the conditions in which an electrode comprising the carbide would be used. For example, metal carbide whiskers of the present disclosure may comprise magnesium carbide, aluminum carbide, titanium carbide, zirconium carbide, hafnium carbide, vanadium carbide, niobium carbide, tantalum carbide, chromium carbide, molybdenum carbide, tungsten carbide, or any mixed metal carbide (e.g., titanium-tantalum carbide, aluminum-titanium carbide, or metal-silicon carbide, such as nickel-silicon carbide). An exemplary current collector is the current collector available from Toyo Aluminum K.K. under the trade name TOYAL-CARBO®.

**[0033]** The metal carbide whiskers may be formed on a variety of metal substrates, which typically include the same metal as the metal carbide whiskers and may include additional metal-containing layers, e.g., layers containing other metals, metal alloys, or metal oxides or hydroxides. For example, as shown in FIG. 1, the current collector **101** includes a cover layer **105** (e.g., a metal oxide layer, such as an aluminum oxide layer) disposed on the first surface **103**. In some embodiments this cover layer **105** may be thin, (e.g., 1  $\mu$ m or less) such that and the elongated metal carbide nanostructures **104** extend through the cover layer **105**.

**[0034]** In some embodiments, a carbonaceous energy storage media **106** is disposed on the first surface **103** or the current collector and in contact with the elongated metal carbide nanostructures **104**. The interface between the nanostructures **104** and the media **106**.

**[0035]** The media **106** may include one or more forms of carbon including activated carbon or nanoform carbon. The language “nanoform carbon” is used herein to describe the general class of allotropes of carbon, which, for example, include but are not limited to nanotubes (single or multi-walled, aligned or unaligned) nanohorns, nano-onions, carbon black, fullerene, graphene, and oxidized graphene. In certain embodiments of the invention the nanoform carbon is a nanotube, e.g., aligned carbon nanotubes.

**[0036]** In some embodiments, the media **106** may be monolithic. In other embodiments, the media **106** may have internal structure, e.g., a plurality of stacked layers.

**[0037]** As shown in FIG. 1, the carbonaceous energy storage media comprises a contact layer **106a** that may include carbon nanotubes. The contact layer **106a** is in contact with the elongated metal carbide nanostructures **104** extending from the first surface **103**.

**[0038]** In some embodiments, the contact layer **106a** may include a compressed layer of carbon nanotubes. For

example, in some embodiments, the nanotubes (e.g., vertically aligned nanotubes) may be grown on a carrier substrate (not shown) and transferred onto the surface **103** using any suitable technique. Exemplary transfer techniques are disclosed in PCT Publication No. WO/2012/170749 published Dec. 13, 2012, and in U.S. Patent Publication No. 2013/0044405 published Feb. 21, 2013 and titled “High Power and High Energy Electrodes Using Carbon Nanotubes,” the entire contents of each of which are incorporated herein by reference. In some embodiments, pressure may be applied during the transfer process to compress the nanotubes. The compressed nanotubes may include physical defects, such as windows and cracks, generally provide more surface area for charge storage, while occupying a smaller volume than the uncompressed material.

**[0039]** In some embodiments, the nanotubes may be aligned in a direction transverse to the first surface **103** (e.g., substantially perpendicular to the surface). In some embodiments, the nanotubes may be aligned in a direction substantially parallel to the first surface **103**. In still further embodiments, the nanotubes may be unaligned or in a combination of various configurations.

**[0040]** In some embodiments, the contact layer **106a** comprises an aggregate of carbonaceous materials, e.g., including carbon nanotubes. In some embodiments, the aggregate may consist essentially of carbon nanotubes. In some embodiments, the aggregate may include carbon nanotubes mixed with a different form of carbonaceous material such as activated carbon or another nanoform carbon material. For example, in some embodiments, the carbon nanotubes may make up less than 90%, 80%, 70%, 60%, 50%, 40%, 30%, 10%, 5%, 2.5%, 1%, or less of the aggregate by weight. In some embodiments, the aggregate may be a dried aggregate, e.g., substantially free of any liquid such as solvents or moisture.

**[0041]** The aggregate may be formed using any suitable technique, such as those described in PCT Publication No. WO/2012/170749. For example, in some embodiments the aggregate may be formed as follows. A first solution (also referred to herein as a slurry) is provided that includes a solvent and a dispersion of carbon nanotubes, e.g., vertically aligned carbon nanotubes. A second solution (also referred to herein as a slurry) may be provided that includes a solvent with carbon disposed therein. The carbon addition includes at least one form of material that is substantially composed of carbon. Exemplary forms of the carbon addition include, for example, at least one of activated carbon, carbon powder, carbon fibers, rayon, graphene, aerogel, nanohorns, carbon nanotubes and the like. While in some embodiments, the carbon addition is formed substantially of carbon, it is recognized that the carbon addition may include at least some impurities, e.g., by design.

**[0042]** Generally, the one or more of the solvents used may be an anhydrous solvent, although this is not a requirement. For example, the solvent may include at least one of ethanol, methanol, DMSO, DMF, acetone, acetonitrile, and the like. Generally, the dispersion of vertically aligned carbon nanotubes may include fragments of vertically aligned carbon nanotubes produced by a production cycle. That is, the vertically aligned carbon nanotubes may be segmented into fragments when harvested from a substrate.

**[0043]** The two solutions may subjected to “sonication” (physical effects realized in an ultrasonic field). With regard to the first solution, the sonication is generally conducted for



a period that is adequate to tease out, fluff or otherwise parse the carbon nanotubes. With regard to the second solution, the sonication is generally conducted for a period that is adequate to ensure good dispersion or mixing of the carbon additions within the solvent.

**[0044]** Once the first solution and the second solution have been adequately sonicated, they are then mixed together, to provide a combined solution and may again be sonicated. Generally, the mixture is sonicated for a period that is adequate to ensure good mixing of the agg vertically aligned carbon nanotube with the carbon addition. This second mixing results in a carbonaceous aggregate.

**[0045]** The carbonaceous aggregate may then be withdrawn from the combined solution and processed. For example, the wet carbonaceous aggregate may be placed onto an appropriate surface. While any material deemed appropriate may be used for the surface, exemplary material includes PTFE as subsequent removal from the surface is facilitated by the properties thereof.

**[0046]** In some embodiments, the carbonaceous aggregate is formed in a press to provide a layer that exhibits a desired thickness, area and density.

**[0047]** In some embodiments, the aggregate may be cast wet directly onto the surface **103a**, and dried (e.g., by applying heat or vacuum or both) until substantially all of the solvent and any other liquids have been removed, thereby forming the contact layer **106a**. In some such embodiments it may be desirable to protect various parts of the current collector **101** (e.g., and underside where the current collector is intended for two sided operation) from the solvent, e.g., by masking certain areas, or providing a drain to direct the solvent.

**[0048]** In other embodiments, the aggregate may be dried elsewhere and then transferred onto the surface **103** to form the contact layer **106a**, using any suitable technique (e.g., roll-to-roll layer application).

**[0049]** In some embodiments the media **106** includes a first overlayer **106b** of carbonaceous material disposed on the contact layer **106a**. In some embodiment, the first overlayer **106b** has a thickness in a direction perpendicular the first surface **103** that is greater than a thickness of the contact layer **106a** along the same dimension (as shown, the vertical direction). In some embodiments, the first overlayer **106b** has a thickness in a direction perpendicular the first surface of in the range of about 1  $\mu\text{m}$  to about 1,000  $\mu\text{m}$ , or any subrange thereof, such as 10-100  $\mu\text{m}$ .

**[0050]** In some embodiments, the overlayer **106b** may include a compressed layer of carbon nanotubes. For example, in some embodiments, the nanotubes (e.g., vertically aligned nanotubes) may be grown on a carrier substrate (not shown) and transferred onto the contact layer **106a** using any suitable technique. Exemplary transfer techniques are disclosed in PCT Publication No. WO/2012/170749 published Dec. 13, 2012, and in U.S. Patent Publication No. 2013/0044405 published Feb. 21, 2013 and titled "High Power and High Energy Electrodes Using Carbon Nanotubes," the entire contents of each of which are incorporated herein by reference. In some embodiments, pressure may be applied during the transfer process to compress the nanotubes. The compressed nanotubes may include physical defects, such as windows and cracks, generally provide more surface area for charge storage, while

**[0051]** In some embodiments, the nanotubes may be aligned in a direction transverse to the first surface **103** (e.g.,

substantially perpendicular to the surface). In some embodiments, the nanotubes may be aligned in a direction substantially parallel to the first surface **103**. In still further embodiments, the nanotubes may be unaligned or in a combination of various configurations.

**[0052]** In some embodiments, the overlayer **106b** comprises an aggregate of carbonaceous materials, e.g., including carbon nanotubes. In some embodiments, the aggregate may consist essentially of carbon nanotubes. In some embodiments, the aggregate may include carbon nanotubes mixed with a different form of carbonaceous material such as activated carbon or another nanoform carbon material. For example, in some embodiments, the carbon nanotubes may make up less than 90%, 80%, 70%, 60%, 50%, 40%, 30%, 10%, 5%, 2.5%, 1%, or less of the aggregate by weight. In some embodiments, the aggregate may be a dried aggregate, e.g., substantially free of any liquid such as solvents or moisture.

**[0053]** The aggregate may be formed using any suitable technique, such as those described in PCT Publication No. WO/2012/170749. The aggregate may wet cast onto the contact layer **106a**, or cast and dried to form the overlay **106b**. The aggregate may be formed as a dry layer transferred onto the contact layer **106a**.

**[0054]** In some embodiments, the overlayer **106b** may be in direct physical contact with contact layer **106a**, e.g., such that no adhesion or bonding layer is disposed therebetween. For example, in some embodiments, the contact layer **106a** and the overlayer **106b** adhere to each other through Van der Waals bonding between carbonaceous material in each layer.

**[0055]** In various embodiments, one more additional overlayers (not shown), comprising carbonaceous material may be stacked over the first overlayer **106b**, e.g., by repeating any of the techniques described above with respect to applying the first overlayer **106b**.

**[0056]** In some embodiments, the electrode **100** may be a two sided electrode, wherein the current collector comprises a second surface, e.g., a lower surface, having a similar structure and energy storage media disposed thereon.

**[0057]** In various embodiments, the presently disclosed electrodes comprise a current collector having a metal carbide layer on at least one surface and CNTs disposed on the metal carbide layer. FIGS. 2A-2D depict various electrodes **1** according to the present disclosure. FIG. 2A depicts certain embodiments in which the electrode comprises horizontally aligned CNTs **6** disposed on a layer of metal carbide whiskers **5** on a surface of a current collector **2**. Current collector **2** may comprise a conducting layer **3** and an oxide layer **4**. Conducting layer **3** may be selected from any material with acceptable electrical and mechanical properties for a particular application, such as conductivity, stability, electrochemical reactivity, hardness, tear resistance, and processability. Conducting layer **3** is typically selected from a variety of conducting metals, such as aluminum, or metal alloys. Oxide layer **4** may be present or absent, but is typically present when conducting layer **4** comprises as oxidizable metal such as aluminum. Metal carbide whiskers **5** are generally a nanostructured metal carbide that are connected to conductor layer **3** of current collector **2** and, when oxide layer **4** is present, extend through oxide layer **4**. CNTs, which are shown as horizontally aligned CNTs **6** in FIG. 2A, adhere to metal carbide whiskers **5**, e.g., through Van der Waals forces. Metal carbide whiskers **5** provide for improved electrical contact between the CNTs and conduct-



ing layer 3, enabling a reduction in the intrinsic resistance of the electrode, while maintaining good adhesion between the current collector 2 and the CNTs 6, when compared to an electrode having an analogous current collector without metal carbide whiskers.

**[0058]** FIG. 2B depicts certain embodiments in which the electrode comprises vertically aligned CNTs 7. FIG. 2C depicts certain embodiments in which the electrode comprises non-aligned CNTs 8, such as tangled or clustered CNTs. FIG. 2D depicts certain embodiments in which the electrode comprises compressed CNTs 9, which may be horizontally aligned CNTs or vertically aligned CNTs that are compressed before or after disposing them onto current collector 2. Generally, compressed CNTs have a higher specific surface area ( $\text{m}^2/\text{g}$ ) than the corresponding uncompressed CNTs. U.S. Patent Publication No. 2013/0044405 published Feb. 21, 2013 and titled “High Power and High Energy Electrodes Using Carbon Nanotubes,” the entire disclosure of which is incorporated herein by reference, discloses compressed CNTs and methods of fabricating electrodes comprising compressed CNTs that may be employed to construct electrodes according to the present disclosure. Specifically, paragraphs [0028] to [0038] and U.S. Patent Publication No. 2013/0044405 and the related figures describe, among other things, electrodes comprising compressed CNTs and methods of fabricating such electrodes.

**[0059]** In certain embodiments, the current collector comprises aluminum carbide whiskers (analogous to metal carbide whiskers 5) on an aluminum current collector (analogous to current collector 2) having a conducting layer of aluminum (analogous to conducting layer 3) and a layer of aluminum oxide (analogous to oxide layer 4). An exemplary current collector is the current collector available from Toyo Aluminum K.K. under the trade name TOYAL-CARBO®. The aluminum carbide “whiskers” are typically <50 nm, <30 nm, or about 20-30 nm in diameter.

**[0060]** As used herein, the term “ultracapacitor” should be given its ordinary and customary meaning to those skilled in the art and refers, without limitation, to an energy storage device also known as a “supercapacitor” and sometimes as an “electric double layer capacitor.”

**[0061]** Ultracapacitors are disclosed herein, which employ the electrodes disclosed herein. The ultracapacitors disclosed herein are exemplary energy storage devices in which the electrodes disclosed herein may be employed. Other energy storage devices, including electrolytic capacitors and rechargeable batteries, that comprise the electrodes disclosed herein are also contemplated by this disclosure, and can be constructed by adapting existing fabrication methods.

**[0062]** In certain embodiments, an ultracapacitor may be formed comprising an electrode of the type described herein. The ultracapacitor may further comprise an electrolyte with certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or separator. In certain embodiments, the electrolyte is a solution comprising at least one inorganic or organic salt, such as an ionic liquid, and optionally further comprising at least one solvent. In certain embodiments, the electrolyte is a gel comprising at least one ionic liquid and at least one gelling agent, and optionally comprising other additives such as solvents, salts, and surfactants. In certain embodiments, the electrolyte is a solid polymer electrolyte comprising at least one inorganic

or organic salt, such as an ionic liquid, and at least one polymeric material, such as a fluoropolymer (e.g., polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK), polyvinylidene difluoride (PVDF), or co-polymers thereof) and optionally comprising other additives such as solvents, salts, and surfactants. In a particular embodiment, the electrolyte is substantially free of moisture and other contaminants that may adversely affect the performance of the ultracapacitor.

**[0063]** The ultracapacitor may further comprise a separator to provide electrical separation between a positive electrode and a negative electrode of the ultracapacitor, which separator has certain desired properties in terms of the electrical performance and compatibility with the other materials of the ultracapacitor, e.g., the electrode or electrolyte. In certain embodiments, the separator comprises a material selected from the group consisting of polyamide, PTFE, PEEK, PVDF, aluminum oxide ( $\text{Al}_2\text{O}_3$ ), fiberglass, fiberglass reinforced plastic, or any combination thereof. In a particular embodiment, the separator is substantially free of moisture. In another particular embodiment, the separator is substantially hydrophobic. In some embodiments, (e.g., where a solid state electrolyte use used that may operate to separate the electrodes of the device), a separator may be omitted.

**[0064]** FIG. 6 shows an exemplary implementation of an ultracapacitor 10 (note, for FIG. 6 like reference numerals do not indicate correspondence to equivalent elements in other figures). In this case, the ultracapacitor 10 is an electric double-layer capacitor (EDLC). The EDLC includes at least one electrode 3, e.g., of the types described in detail above (in some cases, such as where there are two electrodes 3, the electrodes may be referred to as a negative electrode 3 and a positive electrode 3). When assembled into the ultracapacitor 10, each electrode 3 presents a double layer of charge at an electrolyte interface. In some embodiments, a plurality of electrodes 3 is included. However, for purposes of discussion, only two electrodes 3 are shown. As a matter of convention herein, at least one of the electrodes 3 uses a carbon-based energy storage media 1 (as discussed further herein) to provide energy storage.

**[0065]** Each of the electrodes 3 includes a respective current collector 2 (also referred to as a “charge collector”). The electrodes 3 are separated by a separator 5. In general, the separator 5 is a thin structural material (usually a sheet) used to separate the electrodes 3 into two or more compartments.

**[0066]** At least one form of electrolyte 6 is included, and fills void spaces in and between the electrodes 3 and the separator 5. In general, the electrolyte 6 is a substance that dissociates into electrically charged ions. A solvent that dissolves the substance may be included in some embodiments. A resulting electrolytic solution conducts electricity by ionic transport.

**[0067]** Generally, a combination of the electrode(s) 3 and the separator 5 are then formed into one of a wound form or prismatic form which is then packaged into a cylindrical or prismatic housing 7. Once the electrolyte 6 has been included, the housing 7 is hermetically sealed. In various examples, the package is hermetically sealed by techniques making use of laser, ultrasonic, and/or welding technologies. The housing 7 (also referred to as a “enclosing body” or “case” or by other similar terms) includes at least one terminal 8. Each terminal 8 provides electrical access to



energy stored in the energy storage media 1, generally through electrical leads (not shown) which are coupled to the energy storage media 1.

[0068] That is, in some embodiments, a plurality of leads (not shown) are electrically coupled to each of the current collectors 2. Each plurality (accordingly to a polarity of the ultracapacitor 10) are grouped and coupled to respective terminals 8 of the housing 7.

[0069] Additional exemplary suitable implementations of ultracapacitors that may include electrodes of the type described in the present disclosure are disclosed in PCT Publication Number WO/2015/102716 published Jul. 9, 2015, and entitled “ADVANCED ELECTROLYTES FOR HIGH TEMPERATURE ENERGY STORAGE DEVICE,” the entire contents of which are incorporated herein by reference.

[0070] FIGS. 3 to 5C show experimental results for exemplary ultracapacitors of the type described here. FIG. 3 shows a conventional Nyquist plot for an ultracapacitor of the type described herein showing excellent performance.

[0071] FIG. 4A and FIG. 4B are, respectively, plots of capacitance and phase versus frequency for an ultracapacitor of the type described herein having an electrode featuring an electrode comprising a 50  $\mu\text{m}$  aluminum foil with aluminum carbide whiskers and a carbon nanotubes layer disposed thereon. The ultracapacitor shows good capacitive behavior up to a cutoff frequency of about 10 Hz. FIG. 4C shows cyclic voltammetry results for the same ultracapacitor, showing a good operation voltage window ranging from 0V to more than 3V.

[0072] FIGS. 5A, 5B, and 5C show a performance comparison for ultracapacitors of the type described herein having an electrode featuring either an electrode comprising a 50  $\mu\text{m}$  aluminum foil with aluminum carbide whiskers and a carbon nanotubes layer disposed thereon or a similar electrode without any carbon nanotubes. As will be apparent to one skilled in the art, the nanotube-based electrode shows substantially better performance than the electrode lacking nanotubes.

[0073] Having disclosed aspects of embodiments of the production apparatus and techniques for fabricating aggregates of carbon nanotubes, it should be recognized that a variety of embodiments may be realized. Further a variety of techniques of fabrication may be practiced. For example, steps of fabrication may be adjusted, as well as techniques for joining, materials and chemicals used and the like.

[0074] As a matter of convention, it should be considered that the terms “may” as used herein is to be construed as optional; “includes,” “has” and “having” are to be construed as not excluding other options (i.e., steps, materials, components, compositions, etc., . . . ); “should” does not imply a requirement, rather merely an occasional or situational preference. Other similar terminology is likewise used in a generally conventional manner.

[0075] While the invention has been described with reference to exemplary embodiments, it will be understood that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. For example, in some embodiments, one of the foregoing layers may include a plurality of layers there within. In addition, many modifications will be appreciated to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the

invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

1. An electrode comprising:
  - a current collector comprising:
    - a conductor layer having at least a first surface; and
    - elongated metal carbide nanostructures extending from the first surface; and
  - a carbonaceous energy storage media disposed on the first surface and in contact with the elongated metal carbide nanostructures.
2. The electrode of claim 1, wherein the current collector comprises a cover layer disposed on the first surface, and wherein the elongated metal carbide nanostructures extend through the cover layer.
3. The electrode of claim 1, wherein the carbonaceous energy storage media comprises carbon nanotubes.
4. (canceled)
5. The electrode of claim 1, wherein the carbonaceous energy storage media comprises a contact layer comprising carbon nanotubes in contact with the elongated metal carbide nanostructures extending from the first surface, and wherein the contact layer comprises a compressed layer of carbon nanotubes.
- 6-7. (canceled)
8. The electrode of claim 5, wherein the contact layer comprises an aggregate of carbon nanotubes, wherein the aggregate of carbon nanotubes is a dried aggregate that is substantially free of any liquid.
- 9-13. (canceled)
14. The electrode of claim 5, wherein the elongated metal carbide nanostructures extend through the contact layer.
15. The electrode of claim 5, further comprising a first overlayer of carbonaceous material disposed on the contact layer.
16. The electrode of claim 15, wherein the first overlayer has a thickness in a direction perpendicular the first surface that is greater than a thickness of the contact layer along the same dimension.
17. The electrode of claim 15, wherein the contact layer has a thickness in a direction perpendicular the first surface of less than about 5  $\mu\text{m}$ .
18. The electrode of claim 15, wherein the contact layer has a thickness in a direction perpendicular the first surface of less than about 10  $\mu\text{m}$ .
19. The electrode of claim 15, wherein the first overlayer has a thickness in a direction perpendicular the first surface of in the range of about 10  $\mu\text{m}$  to about 1,000  $\mu\text{m}$ .
20. The electrode of claim 15, wherein the first overlayer comprises carbon nanotubes.
- 21-30. (canceled)
31. The electrode of claim 15, wherein no adhesion or bonding layer is disposed between the contact layer and the first overlayer and wherein the contact layer and the overlayer adhere through Van der Waals bonding between carbonaceous material in each layer.
- 32-35. (canceled)
36. The electrode of claim 1, wherein the elongated metal carbide nanostructures comprise nanorods each having a radial thickness of less than 50 nm and a longitudinal length of greater than 500 nm.

**37-39.** (canceled)

**40.** An ultracapacitor comprising:

at least one electrode comprising:

a current collector comprising:

a conductor layer having at least a first surface; and  
elongated metal carbide nanostructures extending from  
the first surface; and

a carbonaceous energy storage media disposed on the first  
surface and in contact with the elongated metal carbide  
nanostructures.

**41-76.** (canceled)

**77.** The ultracapacitor of claim **40**, wherein the current  
collector comprises a cover layer disposed on the first  
surface, and wherein the elongated metal carbide nanostruc-  
tures extend through the cover layer.

**78.** The ultracapacitor of claim **40**, wherein the carbona-  
ceous energy storage media comprises carbon nanotubes.

**79.** The ultracapacitor of claim **40**, wherein the carbona-  
ceous energy storage media comprises a contact layer com-  
prising carbon nanotubes in contact with the elongated metal  
carbide nanostructures extending from the first surface, and  
wherein the contact layer comprises a compressed layer of  
carbon nanotubes.

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