

NON-WOVEN FIBROUS MATERIALS AND ELECTRODES THEREFROM

TECHNICAL FIELD

[0001] The present invention relates to fibrous materials composed of activated carbon fibers and to methods for their preparation. The activated carbon fibers may be used in all manner of devices that contain activated carbon materials, including but not limited to various electrochemical devices (e.g., capacitors, batteries, fuel cells, and the like), hydrogen storage devices, filtration devices, catalytic substrates, and the like.

INTRODUCTION

[0002] Electric double layer capacitor designs rely on very large electrode surface areas, which are usually made from "nanoscale rough" metal oxides or activated carbons coated on a current collector made of a good conductor such as aluminum or copper foil, to store charge by the physical separation of ions from a conducting electrolyte salt into a region known as the Helmholtz layer. This Helmholtz layer, which forms for a few Angstroms beyond the electrode surface, typically corresponds to the first two or three molecules from the surface. There is no distinct physical dielectric in an EDLC, which is provided instead by the electromagnetically determined Helmholtz layer. Nonetheless, capacitance is still based on a physical charge separation across an electric field. Because the electrodes on each side of the cell store identical but opposite ionic charges at their surfaces while the electrolyte between them (but beyond the Helmholtz layer) is depleted and, in effect, becomes the opposite plate of a conventional capacitor, this technology is called electric double layer capacitance. The electrodes are physically separated by a porous thin film spacer similar to electrolytic capacitors or lithium ion batteries. Present EDLCs have frequency response (response curve or RC) constants ranging from milliseconds to seconds.

However, commercial EDLCs (sometimes called ultracapacitors) are presently too expensive and insufficiently energy dense for applications such as hybrid vehicles and are used instead primarily in consumer electronics for fail-soft memory backup.

[0003] It is generally accepted that EDLC carbon surface pore size should be at least about 1-2 nm for an aqueous electrolyte or about 2-3 nm for an organic electrolyte to accommodate the solvation spheres of the respective electrolyte ions in order for the pores to contribute surface available for Helmholtz layer capacitance. Pores also should be open to the surface for electrolyte exposure and wetting, rather than closed and internal. At the same time, the more total open pores there are just above this threshold size the better, as this maximally increases total surface area. Substantially larger pores are undesirable because they comparatively decrease total available surface. Research by others has shown that capacitance improves as average pore size increases from about 4 to about 20 nm

[0004] Conventional activated carbons used in such ELDC devices have many electrochemically useless micropores (i.e., below 2 nm according to the IUPAC definition). The pore size must be approximately the sphere of solvation of electrolyte ions, or larger, for the Helmholtz layer to form. For organic electrolytes, these pores should ideally be larger than 3 to 4 nm. In the best highly activated electrochemical carbons reported in the literature, actual measured EDLC is less than 20% of theoretical due to suboptimal pore size distributions, with a large fraction (typically more than a third to half) being micropores that cannot contribute capacitance and a growing fraction of macropores (depending on degree of activation) that reduce overall surface area. By contract, certain templated carbons with optimal pore sizes and shapes governed by the precursor template material have demonstrated capacitance approaching theoretical values except for losses introduced by the formation of electrode materials made from the carbon particles.

[0005] Performance can be optimized by increasing the useful surface of the carbon sufficiently that both more capacitance and less cost (from less material required) are achieved. In principal, there are two ways that

capacitance can be increased. The primary way is an enhanced effective carbon surface. The IUPAC nanotechnology definition is potentially helpful for organic electrolyte's conventional wisdom on feature dimensions: micropores are $\leq 2\text{nm}$, mesopores are >2 and $\leq 50\text{ nm}$, and macropores are $> 50\text{nm}$. The conventional goal is therefore to generally maximize mesoporous surface.

[0006] The secondary way is formation of electrode materials taking full advantage of the carbon surface that exists. For cost and density reasons, activated carbon powder is commonly packed onto the current collector foil to some depth, typically 50 to 150 microns. To maximize surface, the powder particles need to be randomly packed as tightly as possible. Conventionally, this is done with milled irregular shapes in a particle size distribution ranging over several fold increases in diameter (5 to 20 microns advertised with Kuraray BP20, or 3 to 30 microns with d_{50} of 8 microns according to Maxwell patent 6643119) so that the smaller particles fill voids between larger particles.

[0007] Technically these are polydisperse random packings. Packing density can be adjusted somewhat by the shape of the size distribution. Fines reduce void/volume porosity. Such material voids are commonly thought to be three orders of magnitude larger than the macropores of the IUPAC definition, although technically within it. To eliminate terminological confusion in this discussion, micron scale material voids are called material pores (material porosity) to distinguish from the nanoscale surface pores on or within carbon particles.

[0008] It is useful in this context to introduce a concept, *intrinsic capacitance*, and term, *compaction loss*. Intrinsic capacitance is the ideal capacitance of the total effective carbon surface when fully double layered. The closest measurement to this idea is "carbon Helmholtz capacity" or C_H in $\mu\text{F}/\text{cm}^2$. Kinoshita compiled many reported C_H measurements in Carbon Electrochemical and Physical Properties (1988); more recent papers place the range in organic electrolytes between 3 and 20. Conventional wisdom is that the orientation of graphite crystallite exposed edges plays a role in explaining these differences. Most (if not all) of these C_H measurements are based on

three electrode reference measurements of capacitance and a BET surface estimate and therefore include both compaction loss and any surface measurement error introduced by the BET methodology. Surprisingly, since much activated carbon surface consists of micropores that cannot contribute substantial organic electrolyte capacitance, some of the observed experimental variation in different carbons has to come from the material porosity of the formed electrode material.

[0009] Compaction loss is the difference (in F/g, F/cc, or percent) between the intrinsic capacitance of a carbon and the traditional *specific* capacitance of a somehow formed electrode used as the metric in the industry. Industry experts guesstimate compaction loss ranging from a low of about 30% to over 80%. The actual figure will also vary with electrode thickness for any given material.

[0010] Compaction losses originate from at least five separate phenomena. First, random packing of particles of differing sizes results in highly variable material voids. Such voids are at best long and tortuous, and at worst completely cut off from electrolyte by random restrictions (unwetted surface). Any restriction smaller than about 6nm- easily arising at the conjunction of irregularly shaped interlocking particles ranging from a few tens of nanometers to a few microns diameter-can be shown to result in being completely packed and therefore blocked by adjacent solvated electrolyte ions once a charge is places on the device. No further mass transport or electrolyte diffusion is then possible. Recent research has surprisingly shown that a substantial proportion of a typical activated carbon is actually agglomerations of finer particles produced by activation. One study shows them to average less than 100 nm, but to cluster onto (owing to Van der Waal forces) or to "decorate" micron sized larger particles. The result is that such a restricted region becomes locally depleted of ions, since there is no possibility of further mass transport into the region. The region's surface is underutilized. Second, packing smaller carbon particles into material voids for more surface results in displacing electrolyte from within the material to beyond it, increasing ionic conductivity and mass transport requirements from beyond

the electrode surface, for example from the separator region. In the worse case this limits effective capacitance. In the best case it increases RC and undesirably slows the frequency response of the device. Third, more small particles increase the number of grain boundaries across which electricity must flow in the electrode. That undesirably reduces the conductivity of the electrode, undesirably increases its ESR, and therefore increases its RC. Fourth, to overcome the conductivity problem introduced by many small particles, it is common to add a proportion of conductive carbon particles that do not contribute effective surface. Fifth, to bind such a polydispersion of fine irregular particles together, it is common to add a proportion of a binder such as PTFE that does not contribute to effective surface. Experimental electrodes reported in the scientific literature may have as much as 10% each of conductor carbon and binder, meaning only 80 percent of the electrode mass is capable of contributing effective capacitive surface.

[0011] It is desirable to maximize the performance of EDLCs.

SUMMARY

[0012] The present inventor has found that by forming a fibrous material from activated carbon fiber fragments of substantially similar diameter and aspect ratio α that the performance of EDLCs can be increased.

[0013] In another aspect, the present inventor has found that the performance of EDLCs can also be increased using a fibrous material formed from a mixture of (a) 50 to 95+ % of a first population activated carbon fiber fragments and (b) a second population of carbon fiber fragments of substantially similar or equal diameter to the first population and of longer length than the first population.

BRIEF DESCRIPTION OF DRAWINGS

[0014] Figure 1 is a graph depicting the final volume fractions Φ for the amorphous packings as a function of aspect ratio α . The solid line is a theoretical fit from the random contact equation $\Phi\alpha=5.1$. The inset shows a

magnified view of the same graph at low aspect ratio. Graph reproduced from Physical Review E 67 051301, 051301-5 (2003).

DETAILED DESCRIPTION

[0015] Throughout this description and in the appended claims, the following definitions are to be understood:

[0016] The term “aspect ratio” as used in reference to a carbon fiber or fiber refers to the length of the fiber divided by the diameter of a fiber.

[0017] The term “compaction loss” as used to refer to electrodes refers to the difference (in F/g, F/cc, or percent) between the intrinsic capacitance of a total effective carbon surface and the traditional measured *specific* capacitance.

[0018] The term “intrinsic capacitance” refers to the ideal capacitance of the total effective carbon surface when fully double layered.

[0019] The term “mesoporous” as used in reference to a carbon fiber or fiber describes a distribution of surface feature pore sizes wherein at least about 20% of the total pore volume has a size from about 2 to about 50 nm.

[0020] The phrase “catalytically-activated” as used in reference to a carbon fiber or fiber refers to its pore-containing surface wherein the pores have been introduced by a catalytically controlled activation (e.g., etching) process. In some embodiments, metal oxide particles of a chosen average size serve as suitable catalysts and at least a portion of the metal oxides remain in or on the fibers after the activation process.

[0021] The term “fiber” used in reference to polymers and carbon refers to filamentous material of fine diameter, such as diameters less than about 20 microns, and preferably less than about 10 microns, such as the type that may be obtained using conventional spinning processes.

[0022] The term “nanofiber” used in reference to polymers and carbon refers to a filamentous material of very fine diameter less than 1 micron, and preferably nanoscale (100 nanometers or less in diameter), such as the type that may be obtained using an electrospinning process.

[0023] Activated Carbon Fibers

[0024] Carbon fibers embodying features of the present invention can be prepared by any known process. In general carbon fibers are prepared by polymerizing a monomer to form a polymer fiber and carbonizing at least a portion of the polymer fiber to provide a carbon fiber.

[0025] Carbon fibers can be activated using any known methods. For example, Kyotani, Carbon, 2000, 38: 269-286, have summarized available methods for obtaining mesoporous carbon fibers. Hong et al., Korean J. Chem. Eng., 2000, 17(2), 237-240, described a second activation of previously activated carbon fibers by further catalytic gasification. Preferred methods for preparing carbon fibers with controlled mesoporosity are described in U.S. application serial no. 11/211,894, filed August 25, 2005; the entire contents of that application are incorporated herein by reference. Ideally, one should control the activation of the carbon fiber to ensure mesopore formation, as described in U.S. application serial no. 11/211,894. However, activated carbon fibers formed from other methods of preparation can also be used in this invention.

[0026] In some embodiments, the activated carbon fibers of the present invention comprise diameters of about 10 microns or less, in other embodiments of about 5 microns or less, in other embodiments of about 1 micron or less, in other embodiments of about 500 nm or less, in other embodiments of about 100 nm or less. The preferable diameter depends on the process used to create the fibrous material.

[0027] The activated carbon fibers of the present invention have pores (i.e. they are not smooth surfaces). The size of pores introduced on the fiber surfaces and into the fibers during activation depends on the process, and a preferred embodiment is the catalytic activity of a nanoparticulate metal oxide catalyst, its amount, and/or the size of its nanoparticles as well as the conditions of activation. In general, it is desirable to select pore sizes large enough to accommodate the particular electrolyte used to an optimal surface

packing but substantially larger in order to prevent unnecessary reductions in total fiber surface area.

[0028] The average pore size typically ranges from about 1 nm to about 20 nm. Ideally, the average pore size is from about 3 nm to 15 nm, preferably 6-10 nm.

[0029] Homogenous Carbon Fiber Fragments

[0030] The present invention is based on the realization that a reasonably homogenous population of rod-shaped fragments of carbon fibers can be used to maximize both the surface area and the porosity of a fibrous material formed therefrom. A first surprising aspect of the invention is that both mathematical models and experimental evidence show that low α fibrous materials (short rods, cylinders, or fibers) can randomly pack as densely as spheres. The theoretical three dimensional random packing limit for spheres is 0.64, known as the Bernal limit. Empirically, the Bernal limit is measured at about 0.63 due to inhomogeneous experimental materials. Surprisingly, cylinders with aspect ratio α of 2 have a packing density ϕ of about 0.62. Advantageously for certain materials such as electrodes, they about the same random packing contacts (5.4 ± 0.2 , empirically verified in many experiments) as spheres of equivalent volume (and less than for irregular shapes) but also have more than twice the surface for an equal diameter material, so proportionately fewer points of average contact and potential surface occlusion per unit surface.

[0031] A regular number of contacts on longer conducting elements with reduced numbers of total grain boundaries through the material to the collector foil improves electrical conduction and reduces ESR. The long narrow void channels in cylinder packings have electrolyte diffusion and ionic conductivity advantages, similar to carbon fiber cloth, but without the same material density limitations and at lower cost since the weaving step is avoided. Ordinary carbon papers or felts are comprised of a highly polydisperse aspect ratio distribution of mostly longer fibers that cannot achieve the same random packing density and total surface. Ordinarily, the

expense of manufacturing fiber is rationalized by using its length (for example, for tensile strength or conductive continuity). Surprisingly, the present invention proposes to take advantage only of the cylindrical geometry in short lengths. Since these random packing properties are scale invariant, they can be predictably extended to a second generation of finer fibrous materials.

[0032] During activation, carbon fibers can fragment. For the present invention, the fibers are further fragmented so that the average length of the fibers is relatively homogenous. Fibers can be fragmented using any known means such as chemical or mechanical milling, and screened by means such as advanced air classifiers into particle distributions without excessive polydispersion, for example a distribution of aspect ratios from 1 to 5 but concentrated within 2 to 3. By way of contrast, a typical commercial activated carbon particulate dispersion is from 3 to 30 microns with a median of 8 microns; it is highly polydisperse. The many smaller particles are meant to fit into the voids between the fewer large ones to maximize total surface, but giving rise to compaction loss.

[0033] The carbon fibers embodying features of the present invention may be broken up into shorter fragments (e.g., after carbonization and during or after activation) and then applied to a substrate (e.g., as a slurry) to form a non-woven paper-like layer. A particulate-like short fiber fragment powder may be made from the bulk longer material by crushing, milling, chopping, grinding, chemical milling, etc., with an engineered fragment length distribution for subsequent coating onto a substrate (e.g., an electrode surface).

[0034] In general, the population of fragments for maximal random packing has an average length of one to five times the diameter; that is an aspect of 1 to 5. Aspect ratios less than 1 constitute fines that can "clog" material pores; higher aspect ratios do not pack as densely. An aspect ratio can be selected for a specific device characteristic; for example, for power density more material porosity is desirable to enable electrolyte mass transport (higher ratio), while for energy density more surface from a denser packing might be desirable (lower ratio). In practice, milling and screening

processes result in a particle distribution with some dispersion around the engineering design goal.

[0035] In general, as the diameter of fibers is reduced, increasing their total surface, it becomes more difficult but less important to achieve single digit aspect ratios. Somewhat lower packing density is offset by higher individual fiber surface. To maintain conductivity along the fiber axis and not introduce too many grain boundaries, a practical minimum average length is envisioned. In some embodiments as with 7 micron diameter fiber this length may be 15 micron at an aspect ratio around two. In some embodiments with 5 micron diameter fibers it may be 10 micron length also at aspect ratio 2. For electrospun nanofibers below one micron in diameter, a preferred length may remain a few microns for conductivity, resulting in aspect ratios that increase as fiber diameter decreases. In general, however, aspect ratios for the average material should remain below 20 to achieve reasonable material density greater than about 50%. The engineering tradeoffs are illustrated in Figure 1 which shows theoretical and experimental results for monodisperse packings (taken from Physical Review E 27 051301 (2003)).

[0036] The aspect ratio distribution of the resulting fibrous powder will result in a material of predictable average density and porosity according to these principles of random packing.

[0037] Heterogeneous Mixture of Carbon Fiber Fragments

[0038] It is also within the scope of the present invention to have a multimodal mixture of activated carbon fiber fragments. The first population would comprise fragments with reasonably homogenous lengths and diameters. Other populations of activated fiber fragments would contain substantially the same diameter as the first population, but would have longer lengths and higher aspect ratios.

[0039] As density and total surface are not critically dependent on some long fragments (at substantially higher aspect ratios) in a mix of relatively homogenous smaller ones, it is possible to have a second population of fiber fragments with longer lengths than the first population without substantially

affecting density or surface. Technically, this is a bimodal or multimodal polydispersion. Moderate proportions of longer fibers can be admixed, each averaging 5.4 contacts for each few diameters worth of length. This would have major advantages for material conductivity and ESR by providing semi-continuous conductance pathways and further reducing grain boundary interfaces.

[0040] In one embodiment, the heterogeneous mixture contains from about 50 to 95% of a first population of substantially homogenous (not highly polydisperse) fragments and the balance fragments of substantially similar diameter to the first population, but with longer lengths.

[0041] In one embodiment the length of the fibers in the second population is greater than about twice the length of the first population, in another embodiment the second population is five times as long. In another embodiment, the longer fibers are 50, 100, 150, or 200 microns in average length irrespective of the first population, said lengths corresponding to the desired average thickness of the electrode material.

[0042] Fibrous Materials

[0043] The fibers of the present invention can be further processed to provide a material according to the present invention compatible with conventional particulate carbon coating processes as described in U.S. Patent Nos. 6,627,252 and 6,631,074, the entire contents of both of which are incorporated herein by reference, except that in the event of any inconsistent disclosure or definition from the present application, the disclosure or definition herein shall be deemed to prevail.

[0044] The density of the resulting "paper-like" fibrous material, such as coated onto a current collector foil, is an engineered property of the length of the fiber fragments compared to their diameter (their aspect ratio), the polydisperse distribution of the lengths compared to the average diameter, and optionally post deposition densification (e.g. by pressure). If length approaches diameter, then the fragments will be more like conventional particles and pack more densely with less porosity in the resulting material. If

length is much larger than diameter, then the aspect ratio will be high and packing less dense (i.e. a more porous void to volume ratio material). The average aspect ratio of length to diameter may be adjusted and/or blends of different ratios may be used to provide any material porosity (void/volume ratio) desired within the limits of random packing principals. In some embodiments, at least about 50% of the total number of carbon fiber fragments have a length ranging from about 5 to about 30 microns equivalent to some activated carbon particulate materials. In other embodiments, at least about 50% of the total number of fragments has aspect ratios lower than 30. In other embodiments, average aspect ratios are lower than 20. In other embodiments, average aspect ratios are lower than 10. In other embodiments, where the fiber fragment diameters at or below 100 nm more closely resemble carbon nanotubes, at least about 50% of the total number of carbon fiber fragments are less than 1 micron in length with aspect ratios less than 20.

[0045] In some embodiments, the density of the fibrous material may be further increased (e.g., by simple pressure rolling to a desired thickness or the like). In some embodiments, the density is increased prior to the carbonizing and/or activation, and in other embodiments, the density is increased subsequent to the carbonizing and/or activation. In some embodiments, the thickness of the dense fibrous material is less than or equal to about 200 micron, in other embodiments, less than or equal to about 150 microns, and in other embodiments, less than or equal to about 100 microns.

[0046] Capacitors

[0047] EDLC electrodes are typically made of activated carbon bonded directly or indirectly onto a metal foil current collector, although metal oxides can be used. In accordance with the present invention, activated carbon materials prepared by the methods described herein may be applied to current collectors together with additional metal oxides or the like for hybrid characteristics including enhanced pseudocapacitance.

[0048] A capacitor embodying features of the present invention includes at least one electrode of a type described herein. In some embodiments, the capacitor further comprises an electrolyte, which in some embodiments is aqueous, in other embodiments is organic. In some embodiments, the capacitor exhibits electric double layer capacitance. In some embodiments, particularly when residual metal oxide is present on the surface of the activated carbon fibrous material, the capacitor further exhibits pseudocapacitance.

[0049] Conventional carbon EDLCs with organic electrolytes use either propylene carbonate or acetonitrile organic solvents and a standard fluoroborate salt. Some carbon and most commercial metal oxide EDLCs use aqueous electrolytes based on sulfuric acid (H_2SO_4) or potassium hydroxide (KOH). Any of these electrolytes or the like may be used in accordance with the present invention.

[0050] Since organic electrolytes have lower conductivity than aqueous electrolytes, they have slower RC characteristics and higher ESR contributions, and reach mass transport pore restrictions at substantially larger geometries since they are much larger solvated ions. However, since they have breakdown voltages above 3 V compared to 1 V with aqueous electrolytes, organics produce higher total energy density since total energy is a function of voltage squared. Carbon pores and materials optimized for organics would optionally work for aqueous electrolytes also, since aqueous solvation spheres are smaller. This would allow, for example, ultracapacitor devices to be tailored to RC requirements irrespective of carbon manufacture by changing the electrode packing density via aspect ratio, and by changing electrolyte. Hybrid devices would naturally have a wider range of total RC characteristics since they combine the EDLC with the PC capacitive phenomena. The practical range for use in hybrid electric vehicles is less than about one second to over about 15 seconds, and for distributed power less than about 0.01 seconds to over about 1 second.

[0051] Activated mesoporous carbon fibers or fibers, or their respective fragments, embodying features of the present invention may be incorporated

into all manner of devices that incorporate conventional activated carbon materials or that could advantageously be modified to incorporate fibrous carbon materials of engineered material geometry, surface, porosity, and conductivity. Representative devices include but are not limited to all manner of electrochemical devices (e.g., capacitors; batteries, including but not limited to one side of a nickel hydride battery cell and/or both sides of a lithium ion battery cells; fuel cells, and the like). Such devices may be used without restriction in all manner of applications, including but not limited to those that potentially could benefit from high energy and high power density capacitors or the like.

[0052] The foregoing detailed description has been provided by way of explanation and illustration, and is not intended to limit the scope of the appended claims. Many variations in the presently preferred embodiments illustrated herein will be apparent to one of ordinary skill in the art, and remain within the scope of the appended claims and their equivalents.

CLAIMS

1. A non-woven fibrous material consisting of activated carbon fiber fragments having substantially similar lengths and diameters, wherein the average aspect ratio of the carbon fiber fragment is between about 1 and 20.
2. The non-woven fibrous material of claim 1, wherein the average aspect ratio of the carbon fiber fragment is between about 1 and 10.
3. The non-woven fibrous material of claim 1, wherein the average aspect ratio of the carbon fiber fragment is between about 1 and 5.
4. The non-woven fibrous material of claim 1, wherein the average aspect ratio of the carbon fiber fragment is between about 2 and 3.
5. The non-woven fibrous material of claim 1, wherein the average diameter of the carbon fiber fragment is less than 15 microns.
6. The non-woven fibrous material of claim 1, wherein the average diameter of the carbon fiber fragment is less than 10 microns.
7. The non-woven fibrous material of claim 1, wherein the average diameter of the carbon fiber fragment is about 5 microns.
8. The non-woven fibrous material of claim 1, wherein the compaction loss is less than 50%.
9. The non-woven fibrous material of claim 1, wherein the compaction loss is less than 40%.
10. The non-woven fibrous material of claim 1, wherein the compaction loss is less than 30%.
11. A non-woven fibrous material comprising a first population of activated carbon fiber fragments, wherein greater than about 50% of the first population of activated carbon fiber fragments has substantially similar lengths and diameters, and wherein the average aspect ratio of the first population of activated carbon fiber fragments is between 1 and 20.
12. The non-woven fibrous material of claim 11, further comprising at least a second population of activated carbon fiber fragments whose average lengths exceed those of the first population of activated carbon fiber fragments.

13. The non-woven fibrous material of claim 11, wherein the average aspect ratio of the carbon fiber fragment is between about 1 and 10.
14. The non-woven fibrous material of claim 11, wherein the average diameter of the carbon fiber fragment is less than 15 microns.
15. The non-woven fibrous material of claim 11, wherein the average diameter of the carbon fiber fragment is less than 10 microns.
16. The non-woven fibrous material of claim 11, wherein the compaction loss is less than 50%.
17. An electrode comprising:
 - a current collector; and
 - a non-woven fibrous layer covering at least a portion of the current collector, wherein the non-woven fibrous layer comprising a first population of activated carbon fiber fragments, wherein greater than about 50% of the first population of activated carbon fiber fragments has substantially similar lengths and diameters, and wherein the average aspect ratio of the first population of activated carbon fiber fragments is between 1 and 20.
18. The electrode of claim 17, wherein the non-woven fibrous layer comprising a first population of activated carbon fiber fragments, wherein greater than about 90% of the first population of activated carbon fiber fragments has substantially similar lengths and diameters, and wherein the average aspect ratio of the first population of activated carbon fiber fragments is between 1 and 20.
19. The electrode of claim 17, wherein the thickness of the non-woven fibrous layer is less than or equal to about 200 micron.
20. The electrode of claim 17, further comprising at least a second population of activated carbon fiber fragments whose average lengths exceed those of the first population of activated carbon fiber fragments.