(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
23 October 2008 (23.10.2008)

PCT

(10) International Publication Number
WO 2008/127313 A2

(51) International Patent Classification:
H01L 23/48 (2006.01)

(21) International Application Number:
PCT/US2007/024115

(22) International Filing Date:
19 November 2007 (19.11.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/859,493 17 November 2006 (17.11.2006) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

[Continued on next page]

(54) Title: ELECTRICALLY CONDUCTING AND OPTICALLY TRANSPARENT NANOWIRE NETWORKS

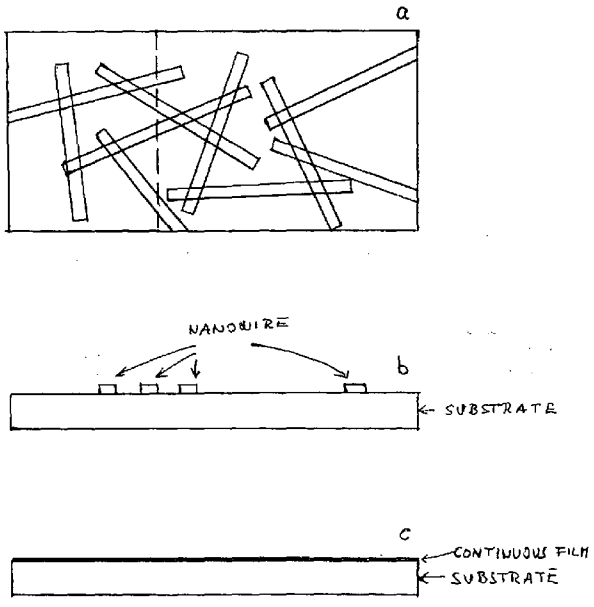


Figure 1

(57) Abstract: A network of nanowires has a plurality of interconnected nanowires. Each interconnected nanowire includes a metal in its composition. The network of nanowires is electrically conducting and substantially transparent to visible light. An electronic or electro-optic device has a network of nanowires. The network of nanowires has a plurality of interconnected nanowires, each interconnected nanowire including a metal in its composition. The network of nanowires is electrically conducting and substantially transparent to visible light. A metal-oxide nanowire has a metal oxide doped with a second metal in a composition thereof. The metal-oxide nanowire is electrically conducting and substantially transparent to visible light.

WO 2008/127313 A2

— *of inventorship (Rule 4.17(iv))*

Published:

— *without international search report and to be republished upon receipt of that report*

ELECTRICALLY CONDUCTING AND OPTICALLY TRANSPARENT NANOWIRE NETWORKS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Application No. 60/859,493 filed November 17, 2006, the entire contents of which are hereby incorporated by reference.

BACKGROUND

1. Field of Invention

This application relates to electrically conducting and optically transparent networks of nanowires, devices made from the nanowires and methods of production.

2. Discussion of Related Art

The contents of all references, including articles, published patent applications and patents referred to anywhere in this specification are hereby incorporated by reference.

Various oxide materials have been used for applications where electrical conductivity and optical transparency in the visible range are required. The current choice of material for such applications is indium-tin-oxide, ITO, that provides optical transmission above 90% with a sheet resistance of less that 100 $(Ohmcm)^{-1}$. While developed to perfection, the material has nevertheless several deficiencies. The material is deposited at high temperature, making compatibility with some (like polymeric) substrates problematic. The difficulty in patterning, together with the sensitivity to acidic and basic environments limits the use in certain applications. Brittleness of the material is obviously an issue for any application for which flexibility is required, and when tailored for such applications the sheet resistance is significantly higher (for the same transmittance) than an ITO film on a rigid substrate such as glass.

Other oxide materials have also been used as transparent coatings and electrodes. As an example, ZnO doped with a variety of dopants has been used in

thin films for in a variety of applications where a transparent and electrically conducting film is required. While a continuous ZnO film doped with Al and other metallic elements has appropriate transparency in the visible spectral range and sheet resistance *(M.K. Jayaray et al Bull. Mat.Soc 25, 227 (2002)*, the material is brittle and thus is not appropriate for applications where mechanical flexibility is required.

Thin films of metals, such as silver are also used as a transparent electronic material. The dc conductivity of good metals such as silver is approximately $6x10^5$ $(Ohmscm)^{-1}$. The components (real and imaginary part) of the optical conductivity have also been evaluated in the visible spectral range (G.R. Parins et al Phys Rev B23, 6408 (1981), R.T. Beach and R.W. Christy Phys Rev B12, 5277 (1977) and references cited therein).

Using these as input and using standard expressions for the optical transparency of thin films of thickness d (M. Dressel and G.Gruner: Electrodynamics of Solids, Cambridge University Press 2002) the sheet resistance and optical transparency in the visible region of the electromagnetic spectrum can be evaluated for films with different thickness. As an example, for a thickness of 5nm, the sheet resistance is 3 ohms (corresponding to a conductivity of $(6 \times 10^5$ Ohmscm$)^{-1}$ and an optical transparency at 550nm wavelength is 90%.

For films where the thickness is significantly smaller that the wavelength of light, the reflectivity is small. There is a well established relation between the optical conductivity σ_{ac} and the optical transmission T

$$T = \frac{1}{(1 + \frac{2\pi}{c}\sigma_{ac}d)^2} \qquad /1/$$

(M. Dressel and G.Gruner: Electrodynamics of Solids, Cambridge University Press 2002), and this relation also describes the parameters quoted above.

Various other electrically conducting materials are also currently developed for plastic, flexible electronics. Most are conducting polymers, and composites, materials that ensure mechanical flexibility, together with electronic conduction. Carbon nanotubes have also been used to fabricate transparent and electrically conducting films (see PCT application PCT/2005/047315 assigned to the same

assignee as the current application). While the materials have the required flexibility, they do not have the sheet resistance and transparency performance required for certain applications.

Consequently, currently there is no material that displays optical transparency and sheet resistance comparable to that of ITO on a rigid substrate, such as glass, having at the same time appropriate mechanical flexibility. There is thus a need for improved optically transparent electrical conductors and devices made therefrom.

SUMMARY

Further objectives and advantages will become apparent from a consideration of the description, drawings, and examples.

A network of nanowires according to an embodiment of the current invention has a plurality of interconnected nanowires. Each interconnected nanowire includes a metal in its composition. The network of nanowires is electrically conducting and substantially transparent to visible light.

An electronic or electro-optic device according to an embodiment of the current invention has a network of nanowires. The network of nanowires has a plurality of interconnected nanowires, each interconnected nanowire including a metal in its composition. The network of nanowires is electrically conducting and substantially transparent to visible light.

A metal-oxide nanowire according to an embodiment of the current invention has a metal oxide doped with a second metal in a composition thereof. The metal-oxide nanowire is electrically conducting and substantially transparent to visible light.

A method of producing an electronic or electro-optic device includes dispersing a plurality of nanowires in a liquid solution, depositing at least a portion of the liquid solution to provide a network of nanowires on a substrate, and transferring the nanowires from the substrate to another substrate to form at least a portion of an electronic or electro-optic device. The nanowires comprise at least one of metal nanowires or metal-oxide nanowires doped with a second metal.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is better understood by reading the following detailed description with reference to the accompanying figures in which:

Figures 1a-1c provides an illustrative example of a nanowire network according to an embodiment of the current invention and also contrasted to a thin film. Figure 1a is the top view of an interconnected network above the percolation threshold, Figure 1b is a cutaway view of the network along the dashed line indicated on Figure 1a, and Figure 1c is a continuous thin film with the same cross sectional area as the network indicated on Figure 1b.

Figure 2 shows the optical transparency versus the sheet resistance of a silver and ZnO nanowire network with parameters as described in the specification according to an embodiment of the current invention.

Figure 3 provides scanning electron microscope images of an electrically conducting silver nanowire network on a substrate according to an embodiment of the current invention. The image on the right clearly shows that the network is transparent.

Figures 4a-4f provides a schematic illustration of producing a nanowire network according to an embodiment of the current invention. Figure 4a is an illustration of a patterned PDMS stamp and nanowire films made by vacuum filtration. Figure 4b shows conformal contact between a PDMS stamp and nanowire films on the filter. Figure 4c shows that after the conformal contact, the PDMS stamp is removed from the filter. Patterns of nanowire films are transferred onto the PDMS stamp without any damage. Figure 4d shows a PDMS stamp with patterned nanowire films and a flat receiving substrate. Figure 4e shows conformal contact between a PDMS stamp and the substrate. Figure 4f shows that after removing the PDMS stamp from the substrate, all patterned nanotube films on the stamp are fully transferred onto the substrate.

Figure 5 is an illustration of the top view of two interpenetrated nano-structure networks

according to an embodiment of the current invention.

Figure 6 shows a multilayer structure that incorporates a substrate, a nanowire network and an encapsulation layer according to an embodiment of the current invention.

Figure 7 is a schematic illustration of a multilayer structure that includes a substrate, a "functional layer", and a nano-structure or multiple nano-structure network.

Figure 8 is a schematic illustration of an architecture that incorporates a substrate, a nanowire network, a "functional component" such as a chemical or nano-structured material and an encapsulation layer according to an embodiment of the current invention. Such a structure can alleviate the problem of easy removal of or damage to the "functional material" by encapsulating the (nanotube + functional material) with a layer.

Figure 9 is a schematic illustration of an architecture for a supercapacitor using structured Ag nanowire Electrodes according to an embodiment of the current invention. Both the substrate and the electrolyte can be a polymer electrolyte for an entire solid state device. The Ag nanowire electrodes can be completely embedded in the electrolyte.

Figure 10 shows a cyclovoltammogramm of a silver nanowire network supercapacitor as illustrated in Figure 9.

Figure 11 is a schematic illustration of a solar cell that has a nanowire network according to an embodiment of the current invention.

Figure 12 is a schematic illustration of a light emitting diode that has a nanowire network according to an embodiment of the current invention.

Figure 13 is a schematic illustration of a battery that has a nanowire network according to an embodiment of the current invention.

DETAILED DESCRIPTION

In describing embodiments of the present invention illustrated in the drawings, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. It is to be understood that each specific element includes all technical equivalents which operate in a similar manner to accomplish a similar purpose.

Some embodiments of the current invention are directed to a random network of transparent oxide and/or metal nanowires. An example of transparent oxide nanowires according to some embodiments of the current invention include, but are not limited to, doped ZnO. An example of metal nanowires according to some embodiments of the current invention includes, but is not limited to, silver (Ag) nanowires. A random network, while retaining the high conductivity and optical transparency also has mechanical flexibility. In addition, the one dimensional nature of the nanowires leads to increased optical transparency compared to a continuous, three dimensional material such as a film.

A random assembly of nanowires on a substrate can also be viewed as a new electronic material that offers several fundamental advantages for flexible electronics applications. These are derived from the architecture itself, from the attributes of the constituent wires, from the ease of fabrication, and compatibility with other materials such as polymers. The material's architecture is illustrated schematically in Figure 1. With components that are conductors or semiconductors, such a two dimensional (2D) nanowire network is a conducting medium with several attractive attributes. 1. *Electrical conductance.* This value proposition assumes that the conductivity of the wires is large; the larger the nanowire conductivity, the better the network conductance. 2. *Optical transparency.* With ZnO, a transparent material, high optical transparency is also achieved even for a continuous film. However, high transparency is expected for other electrically conducting nanowires as well. A network of highly one-dimensional wires has high transparency, approaching 100%, for truly one-dimensional wires with aspect ratio approaching infinity. This is in contrast to networks formed of nanoparticles, for example, where substantial coverage of the

surface – and thus small optical transparency – is needed for electrical conduction. 3. *Flexibility.* A random network of wires has, as a rule, significantly higher mechanical flexibility that a film, making the architecture eminently suited in particular for flexibility-requiring applications. 4. *Fault tolerance.* Breaking a conducting path leaves many others open, and the pathways for current flow will be rearranged. The concept, called fault tolerance, is used in many areas, from internet networks to networks of power lines. The same concept applies here as well.

1. Modeling of the electrical and optical properties of Ag nanowire networks.

As a feature of the present invention, the nanowires that form the networks have diameters of less than 100 nm and aspect ratios of at least 10. The relationship between conductivity, sheet conductance and optical transparency is as follows.

The nanowire density of the nanowire network on a surface can be described by either:

- average network thickness, d
- nanotube surface density, sd or nanotube coverage c of the surface that supports the network

100% coverage of a network leads to an average thickness equivalent to the diameter of the nanowires, this also corresponds to a surface density of 100%. Networks with more or less that 100% coverage can be fabricated and are included within the scope of the current invention.

The dc, direct current conductivity σ_{dc} is a parameter that is independent of the nanowire density. The sheet conductance, the technically important parameter, is given by σ_{dc} d. Various factors determine the dc conductivity:

- number of charge carriers (electrons or holes)
- number of nanowire-nanowire interconnects per unit area
- nanowire-nanowire interconnect resistance

Forming nanowires and assuming that the electrical and optical properties of the individual wires are the same as that of a continuous film leads to the following

estimate for the sheet resistance and optical transmission of a nanowire network. An illustrative example of an interconnected network of nanowires is shown on Figure 1. First one notes that a network made of a 50nm x 50nm nanowires that covers, say 10% of the surface leads to the same optical absorption as that of a continuous film of 5nm, i.e. 90%, due to the fact that the absorption is determined by the number of Ag atoms per unit area in the structure. If the nanowire network is grained so that the network, in a surface area determined by the length scale of the light, (typically 550 nm, a characteristic wavelength in the visible spectral range) contains a large number of nanowires the reflectivity will also be close to the reflectivity of a continuous film that has the same thickness as the average thickness of the nanowire network. Thus the optical transparency of the network of 50nm x 50nm wires that cover 10% of the surface has the same transparency as a 5nm thick continuous film. Given the fact that the dc conductivity is given by

$$\sigma = \frac{1}{R}\frac{\ell}{A} \qquad /2/$$

where R is the measured resistance, l is the length and A is the cross section, is inversely proportional to the cross sectional surface area of the conducting structure, the dc conductivity of the network is also the same as the continuous 5nm thick film if the electrical conductivities of a film and a network are the same – assuming that the conductivities of a film and nanowires are the same.

The sheet resistance Rs – the resistance of a square shaped film - is given by

$$1/Rs = \frac{1}{Rd} \qquad /3/$$

where d is the thickness of a film – or the average thickness of the network.

The electrical conductivity of silver nanowires is $(0.8 \times 10^5 \text{ Ohmcm})^{-1}$ (Y. Sun et al Chem. Mater. 14, 4736 (2002), 7.5 times smaller than the conductivity of a silver film, reflecting effects such as surface scattering. The optical conductivity is not affected by these factors and is the same or close to that of films of silver. Consequently, an interconnected network of nanowires is expected to have an optical transmission of 90% of the sheet resistance Rs of 3x 6/0.8= 21.2 Ohms. Equation /1/

above can then be used to establish a sheet resistance to optical transparency relation for Ag nanowire networks at different densities. This is shown on Figure 2, using R=21 Ohms and T=90 % as input parameters, by the dashed line incorporating the diamond symbols. The estimates given in the text and displayed on Figure 2 are in agreement with recent calculations involving silver metal gratings (M. Kang et al Adv. Mat 19, 1301 (2007)).

The data in Figure 1 demonstrates that a random network of Ag nanowires can be used as a transparent electronic material.

For randomly arranged nanowires an additional factor plays a role, further reducing the optical absorption and enhancing the transmission T. Only the component of the light polarized along the direction of the wires is effective. The absorbed power of electromagnetic radiation W, the loss, is simply given by

$$W = 1/3\ V\sigma_1 E^2 \qquad /2/$$

where V is the volume occupied by the collection of nanowires, σ_1 is the real part of the optical conductivity, the factor 1/3 coming from the random orientations with respect to the applied electric field E_0. (The above expression is valid in the limit when the skin depth is larger that the cross section of the nanowire, an obviously satisfied condition for nanowires less than 100 nm thickness.) This effect will reduce the optical absorption and consequently increase the optical transparency, further improving the useful parameters for the material as a transparent electrical conductor. The dashed line incorporating the diamond symbols is expression /1/ normalized to T=90% and Rs=21.2 Ohms.

2. Modeling of ZnO networks

The parameters of ZnO films can be modeled using the parameters for continuous films. A typical 5000 A film has a resistivity of $5x10^{-4}$ Ohms cm and optical transparency of 90% *(M.K. Jayaray et al bull Mat. Sci. 25, 227 (2002), H.Kim et al Appl.Phys.Lett 76, 259 (2000).* This leads to a resistance of 10 Ohms for a

network with an overall thickness of 5000 A. The argument advanced above leads therefore to a sheet resistance–optical transmission relation similar to for the Ag films described above. This is also displayed on Figure 2 with the dashed lines incorporating the solid squares. derived by assuming that ZnO nanowires have the same resistance as a ZnO film.

The data in Figure 2 demonstrates that a random network of ZnO nanowires can be used as a transparent electronic material.

2. Formation of Ag nanowire networks

Silver nanowires can be prepared using various preparation routes (E.A. Hernandez et al Nanotech 2004 Vol 3 Ch4 p156, A.Graff et al Eur. Phys. J. D. 34, 263 (2006) Y.Gao et al J.Phys.D. Appl. Phys. 38, 1061 (2005) (Y. Sun et al Chem. Mater., 14 (11), 4736 -4745, 2002)). Such wires are typically 50 – 100 nm wide and can have a length exceeding one micron. Such wires are also commercially available.

There are several ways a silver nanowire network can be formed. Nanowire deposition methods may include drop casting, spin coating, roll-to-roll coating and transfer printing. In all cases, nanowires are dissolved in an aqueous liquid. The liquid can be water, alcohol, aromatic solvent or hydrocarbon.

Nanowires are prepared with PVP (polyvinyl pyrrolidone, povidone, polyvidone) wrapped around the nanowires (Y. Sun et al Chem. Mater., 14 (11), 4736 -4745, 2002). PVP is soluble in water and other polar solvents. In water it has the useful property of Newtonian viscosity. In solution, it has excellent wetting properties and readily forms films. This makes it also an excellent coating or an additive to coatings. The polymer, wrapped around the nanowires hampers the propagation of electric charges from nanowire to nanowire, leading to a large resistance of the network. Consequently it has to be removed. This can be accomplished by heat treatment. The thermal gravimetry (TG) curve shows a two-step weight decline pattern with the inflexion points at ≈ 200 and 475°C. The first change corresponds to the removal of the PVP that attached to the Ag nanowires. (Y. Sun et al Chem. Mater., 14 (11), 4736 -4745, 2002). Consequently, a heat treatment at this temperature leads to the removal of PVP and to a nanowire network with high

electrical conductivity – approaching the conductivity, for a certain optical transparency that is given in Figure 2.

3. Transfer printing method of forming nanowire networks

A fabrication method that preserves the exceptional properties of nanowires has been developed. It yields consistently reproducible nanowire films and allows large-scale industrial production. This method combines a PDMS (poly-dimethysiloxane) based transfer-printing technique (N.P. Armitage, J-C P Gabriel and G. Grüner, " Langmuir-Blodgett nanotube films", J. Appl. Phys.. **95**, 3228 Y. Zhou, L. Hu and G. Grüner, "A method of printing carbon nanotube thin films", Appl. Phys. Lett. **88**, 123109 (2006)) for controlled deposition of large area highly conducting carbon nanotube films with high homogeneity on various substrates, including PET (polyethylene), glass, PMMA (polymethyl-methacrylate), and silicon. The films can also be printed in a patterned fashion for use as building blocks in electronic devices.

To prepare nanowire films, nanowires are dispersed in an aqueous solution. The solvent can be water, toluene and other organic and inorganic materials. Then the solution is bath-sonicated, typically for 16 hour at 100 W and centrifuged at 15000 rcf (relative centrifugal field). Alumina filters with a pore size of 0.1-0.2 μm (Whatman Inc.) are suitable to be used in the vacuum filtration. After the filtration, the filtered film is rinsed by deionized water for several minutes. Heat treatment is required to remove the PVP with a temperature between typically 150 and 250 C for several minutes. The sheet resistance can be varied over a wide range by controlling the amount of nanowires used. For networks just above the percolation threshold, the sheet resistance reduces dramatically with the increase of nanotube amount, while in the region far from the threshold, the sheet resistance decreases inversely with the network density, or film thickness, as expected for constant conductivity.

PDMS stamps for transfer printing can be fabricated by using SYLGARD® 184 silicone elastomer kit (Dow Corning Inc.) with silicon substrates as masters. To make patterned PDMS stamps, SU-8-25 resist (MicroChem Inc.) can be spun onto silicon substrates and patterned by standard optical lithography. Silicon masters are

pretreated with two hours of vacuum silanization in the vapor of (Tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane. Subsequently the silicone elastomer base and the curing agent are mixed together with a ratio of 10:1 in this example. After two hours of curing in the vacuum to remove the bubbles, the mixture is cast onto the silicon master, which is followed by one hour of vacuum curing and two hours of oven baking at 65 °C. Finally, the PDMS stamp is removed from the silicon master. Figure 4 illustrates a patterned PDMS stamp, together with the fabrication process.

To remove the nanowire films from the filters, one first makes conformal contact between the stamp and the films on the filter (Figure 4(b)). As soon as the wetting due to the conformal contact is seen, the stamp is raised from the filter and the patterned films are transferred onto the stamp (Figure 4(c)). Transfer of nanowire films from one surface to another surface is guided by surface energies of the two surfaces. Since the nanowire films loosely sit on the alumina filters, they can be fully transferred onto the PDMS surface even though PDMS has a low surface energy of 19.8 mJ/m^2. The same filter can be reused for fabrication of another film.

The availability of patterned nanowire films on PDMS stamps (Figure 4(d)) readily allows them to be printed onto various flat substrates with a higher surface energy, such as PET (44.6 mJ/m^2), glass (47 mJ/m^2), and PMMA (41 mJ/m^2). The surface energy of silicon substrates can be increased by oxygen plasma cleaning and vapor silanization using (aminopropyl)triethoxysilane. To start the transfer, one first contacts the PDMS stamp with nanowire films onto the receiving substrate (Figure 4(e)). After a few minutes of mild heating at 80°C, substantially all nanowire films on the stamp are transferred onto the receiving substrate by simply removing the stamp from the substrate (Figure 4(f)). The smallest pattern size that can be achieved by the printing method according to an embodiment of the invention is 20 μm, limited by the SU-8-25 resist based optical lithography to make the silicon master. Usage of PDMS stamps with smaller feature sizes may lead to patterns of nanowire films with higher resolution. Figure 3(b) shows a photo image of a transparent and homogeneous film with a two-inch diameter on a flexible PET substrate. Recyclable use of filters and stamps may allow utilization of high cost, large area filters and

PDMS stamps at the industrial scale without significantly increasing the fabrication cost of thin films.

4. Multiple networks

Silver nanowire networks can also form part of a network with a multitude of nanoscale components.

Structures within the scope of the current invention include:

1) two or more interpenetrating nano-scale networks as an electronic material (having a finite electronic conduction) and the various methods that may be used to fabricate such networks. The networks can be free-standing or on a substrate. More particularly, some embodiments of the present invention are directed to a multitude of interpenetrating nano-structured networks that are suitable for use in electronic applications, such as resistors, diodes, transistors solar cells and sensors;

2) a three component structure: a (1) substrate and (2) functional layer together with a (3) network or networks of nano-structured materials; and a (1) substrate together with a (2) network or networks of nano-structured materials and an encapsulation layer (3);

3) a four component structure: a (1) network or networks together with a (2) functional material on a (3) substrate and an (4) encapsulation material that prevents the functional material to be removed from the network and substrate, and the various methods that may be used to fabricate such structures that are suitable for use in electronic applications, such as resistors, diodes, transistors solar cells and sensors;

4) combinations of the above.

1. Examples of the nano-scale materials that can form the two nano-structure networks with silver nanowires include

inorganic nanowires,

polymeric nanofibers,

carbon nanotubes,

organic fibers such as that from cloths,

metallic nano-particles,

biological materials, such as a protein or DNA,
nano-structured light sensitive materials, such as a PMPV,
nanoporous materials such as aerogels, carbon black and activated carbon.

2. The encapsulation agent can be a
polymer such as a parylene, a PEDOT:PSS, Poly(3,4 ethylenedioxythiophene)poly(styrenesulphonate)
light sensitive material, such as a poly((m-phenylenevinyle)-co-)2.3.diotyloxy-p-phenylene)), PmPV.

5. Electronic device with Ag nanowire components

Charge storage devices, batteries and capacitors drive a variety of electronic devices and have an increasing role due to portable consumer electronics. Charge storage devices based on nanostructured materials, together with the novel manufacturing route make such devices valuable for a range of applications where portable, light weight, disposable power is required. Such applications include smart cards, functional RFID devices, cheap disposable power sources for portable electronics and wearable electronics.

We have fabricated a charge storage device, a supercapacitor (SC), that incorporates a silver nanowire network, or film, as the charge collector and electrode according to an embodiment of the current invention. Cyclic voltammetry (CV) and galvanostatic charge/discharge experiments were used to determine the capacitance of the nanowire network electrode/charge collector. For all measurements, a computer controlled potentiostat (Jaissle IMP 83-PC, *Jaissle Electronic GmbH, Waiblingen, German)* was used. From the CV, we calculated the specific capacitance c of our device according to $c=i/v$, where v is the scan rate (20mV/s) and i the corresponding current of the voltage applied. It was found that the specific capacitance of our device to be 0.8 F/g at 1 Volt.

The stability of the films was tested with respect to several electrolytes. Table 1 shows the change of the resistance of the films when subjected to the electrolytes. No substantial change is observed as an indication of the absence of significant

chemical reaction between the silver nanowires and the electrolytes. Polymer electrolytes such as described in M. Kaemgen et al Appl. Phys. Lett 90, 264101 (2007) can be equally well applied.

The functional device demonstrates that random networks of nanowires can serve as charge transport supporting layers. Such devices can include solar cells, optical detectors, and batteries. Solar cells can be fabricated following the fabrication described in M.W. Rowell Appl. Phys. Lett. 88, 233506 (2006) and light emitting diodes following the fabrication procedure described in Nano Letter 6, 2472 (2006) in combination with the teachings herein. Batteries can be fabricated following the publication A. Kiebele and G.Gruner Appl. Phys Lett. 91, 144304 (2007) in combination with the teachings herein.

The embodiments illustrated and discussed in this specification are intended only to teach those skilled in the art the best way known to the inventors to make and use the invention. Nothing in this specification should be considered as limiting the scope of the present invention. The above-described embodiments of the invention may be modified or varied, and elements added or omitted, without departing from the invention, as appreciated by those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the claims and their equivalents, the invention may be practiced otherwise than as specifically described.

Table 1

Change of the electrical resistance of Ag nanowre networks when subjected to various chemicals.

Electrolyte	R before (Ohms)	R during (Ohms)
NH4Cl	76.7	62.1
KOH	76	67.2
H3PO4	27.3	24.8
H2O	36.1	32.3

WE CLAIM:

1. A network of nanowires comprising a plurality of interconnected nanowires, each interconnected nanowire comprising a metal in its composition, wherein said network of nanowires is electrically conducting and substantially transparent to visible light.

2. A network of nanowires according to claim 1, wherein said plurality of interconnected nanowires are a plurality of interconnected metal nanowires.

3. A network of nanowires according to claim 2, wherein said metal nanowires are at least one of silver and gold nanowires.

4. A network of nanowires according to claim 1, wherein said plurality of interconnected nanowires are a plurality of interconnected metal-oxide nanowires.

5. A network of nanowires according to claim 4, wherein said metal-oxide nanowires are doped with a second metal.

6. A network of nanowires according to claim 5, wherein said metal-oxide is zinc-oxide and said second metal is aluminum.

7. A network of nanowires according to claim 5, wherein said metal-oxide is tin-oxide and said second metal is indium.

8. An electronic or electro-optic device comprising a network of nanowires, said network of nanowires comprising a plurality of interconnected nanowires, each interconnected nanowire comprising a metal in its composition, wherein said network of nanowires is electrically conducting and substantially transparent to visible light.

9. An electronic or electro-optic device according to claim 8, wherein said

plurality of interconnected nanowires is a plurality of interconnected metal nanowires.

10. An electronic or electro-optic device according to claim 9, wherein said metal nanowires are at least one of silver and gold nanowires.

11. An electronic or electro-optic device according to claim 8, wherein said plurality of interconnected nanowires is a plurality of interconnected metal-oxide nanowires.

12. An electronic or electro-optic device according to claim 11, wherein said metal-oxide nanowires are doped with a second metal.

13. An electronic or electro-optic device according to claim 12, wherein said metal-oxide is zinc-oxide and said second metal is aluminum.

14. An electronic or electro-optic device according to claim 12, wherein said metal-oxide is tin-oxide and said second metal is indium.

15. An electronic or electro-optic device according to claim 8, wherein said electronic or electro-optic device is at least one of a solar cell, a light emitting diode, a battery or a supercapacitor.

16. A metal-oxide nanowire comprising a metal oxide doped with a second metal, wherein said metal-oxide nanowire is electrically conducting and substantially transparent to visible light.

17. A metal-oxide nanowire according to claim 16, wherein said metal oxide is zinc oxide and said second metal is aluminum.

18. A metal-oxide nanowire according to claim 16, wherein said metal oxide

is tin oxide and said second metal is indium.

19. A method of producing an electronic or electro-optic device, comprising:

dispersing a plurality of nanowires in a liquid solution;

depositing at least a portion of said liquid solution to provide a network of nanowires on a substrate; and

transferring said nanowires from said substrate to another substrate to form at least a portion of an electronic or electro-optic device,

wherein said nanowires comprise at least one of metal nanowires or metal-oxide nanowires doped with a second metal.

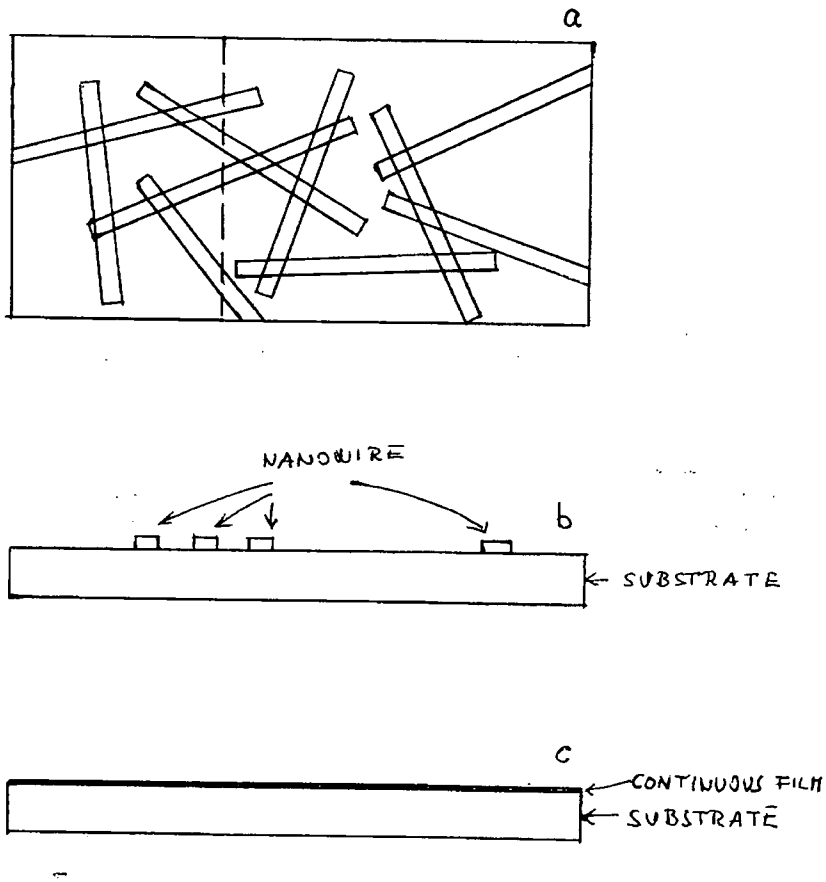


Figure 1

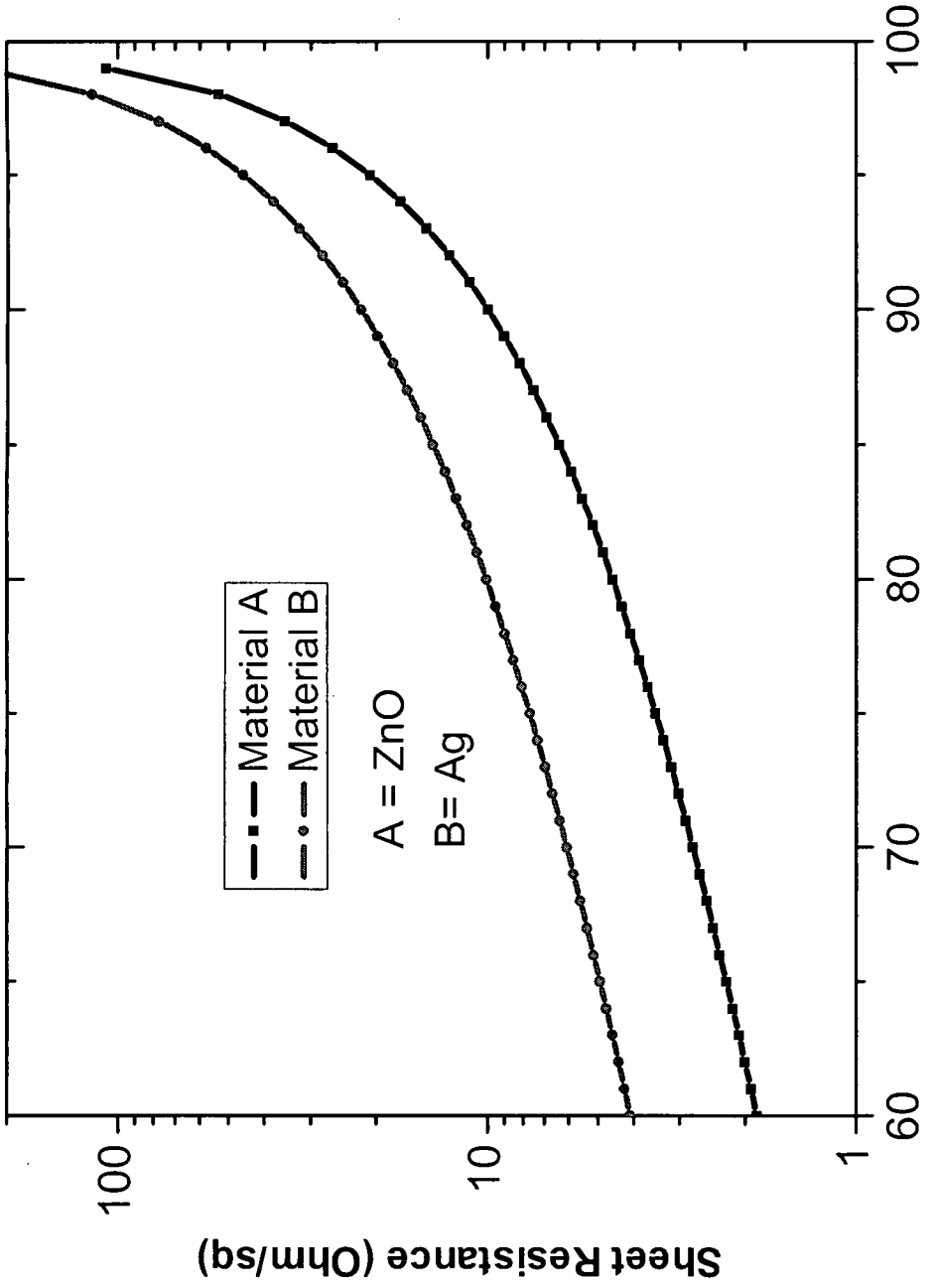


Figure 2
R=22 Ohm/sq with 90%, conductivity 31596
R=10 Ohm/sq with 90%, conductivity 69510

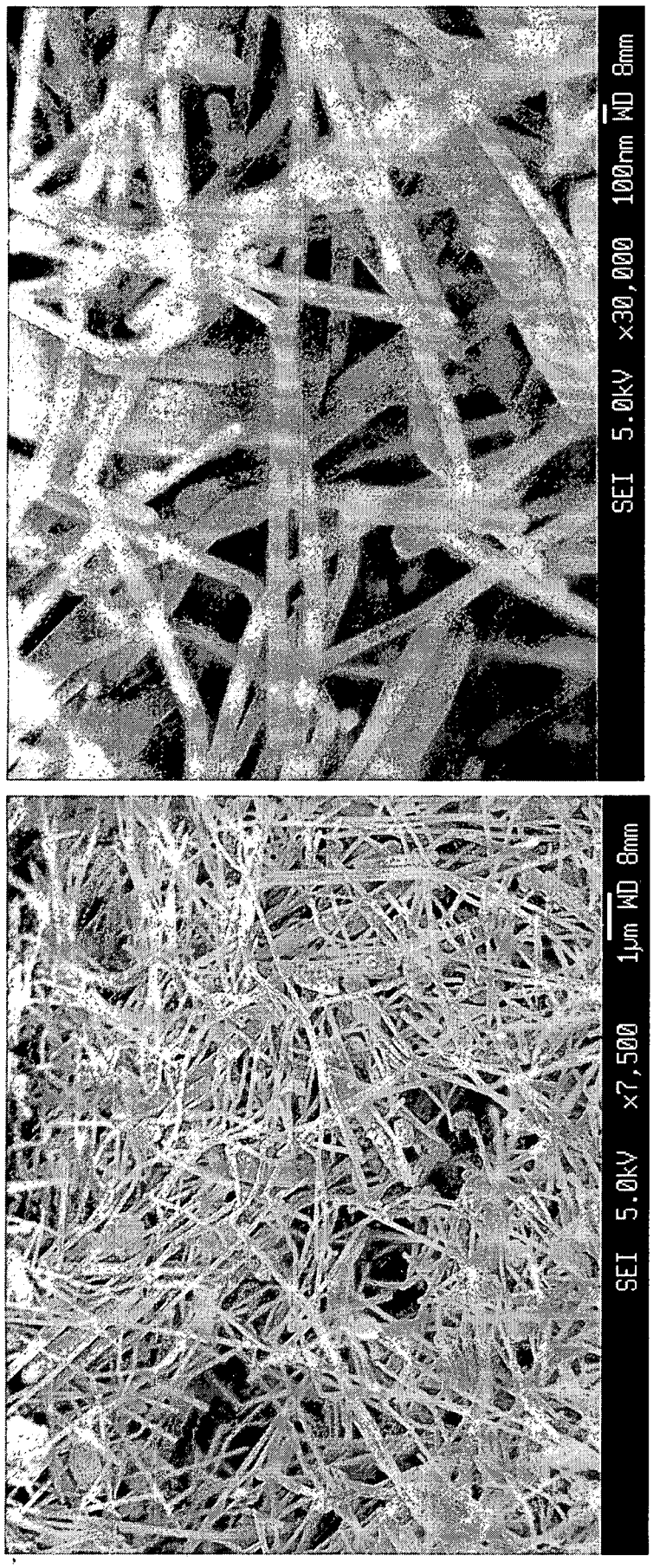
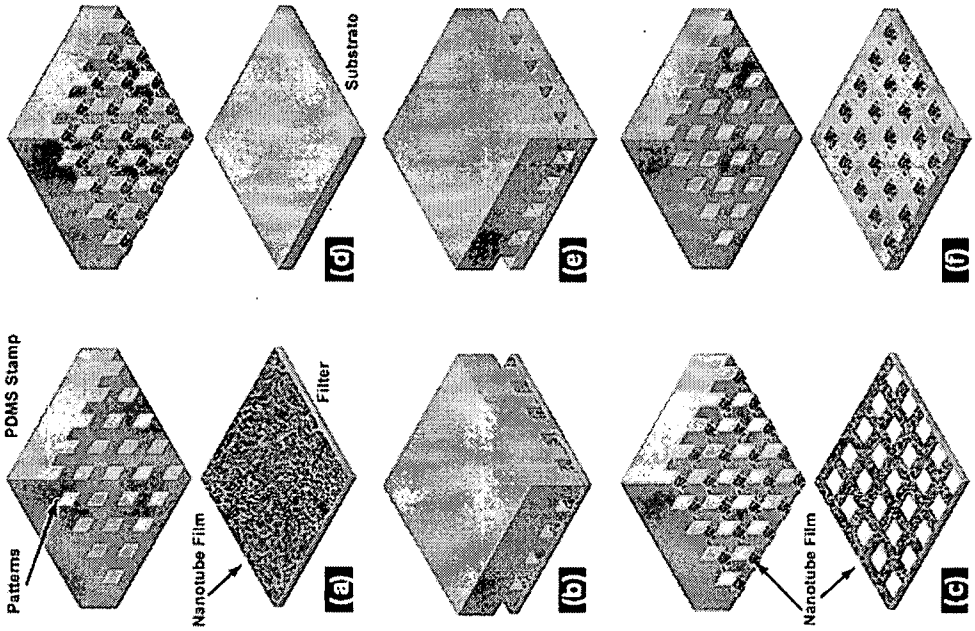


Figure 3

Figure 4


PDMS Stamp
Patterns
Nanotube Film
Filter
Substrate
(a)
(b)
(c)
(d)
(e)
(f)

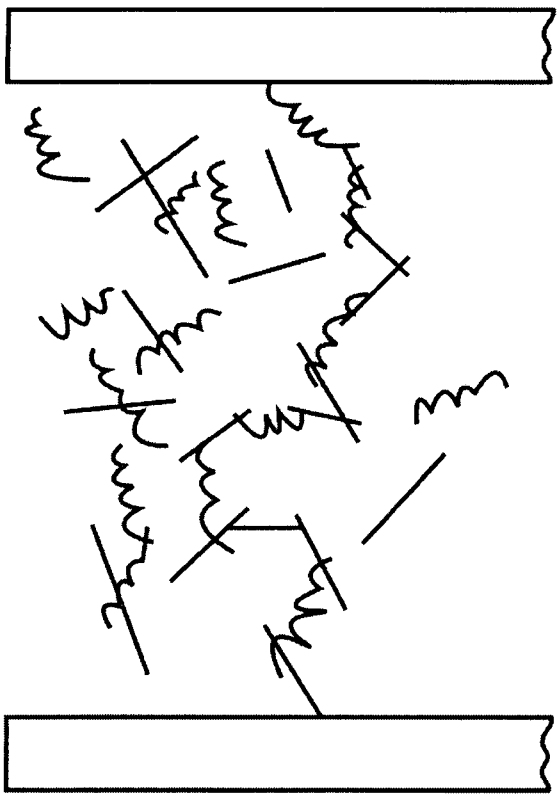


Figure 5

Fig 6

Fig 7

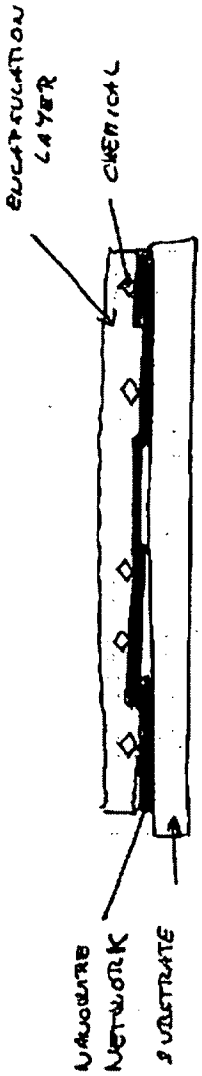
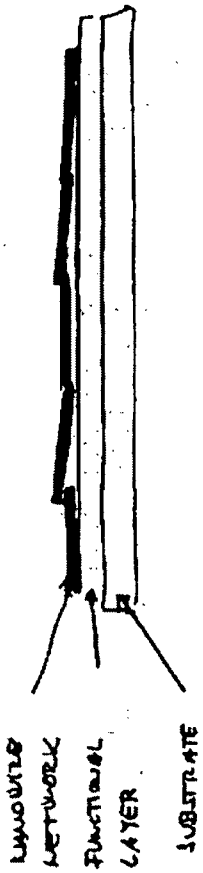


Fig 8



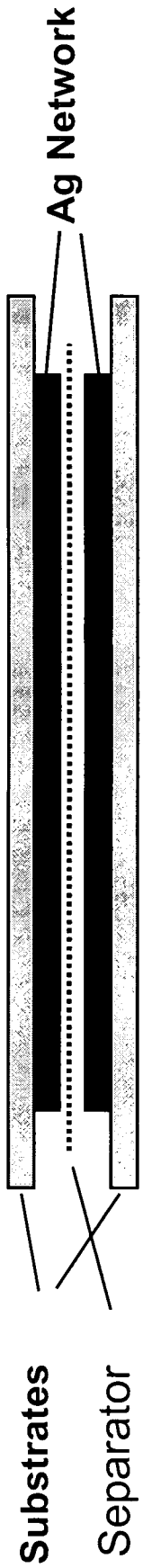


Figure 9

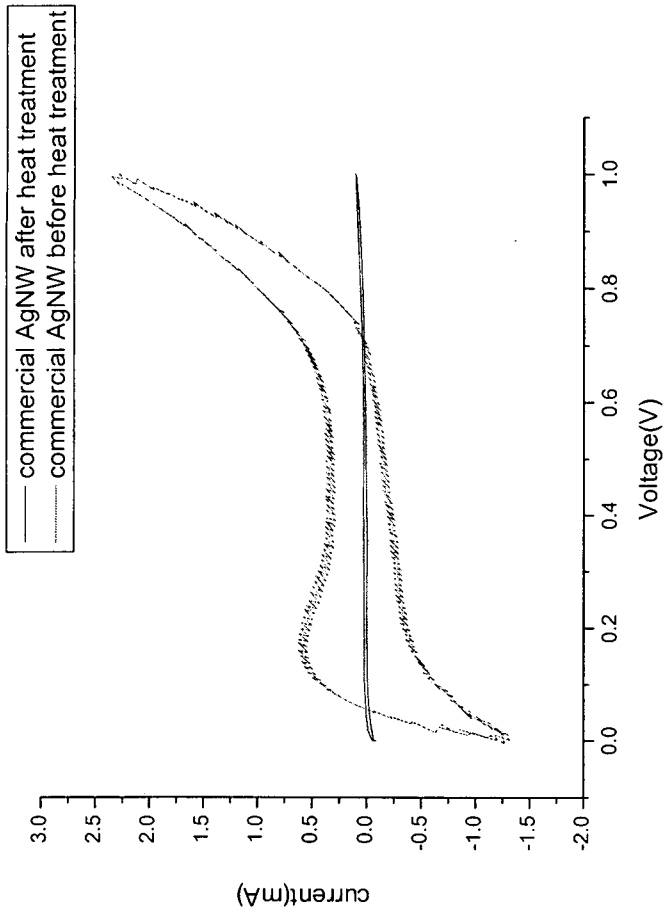

commercial AgNW after heat treatment
commercial AgNW before heat treatment
current(mA)
Voltage(V)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.0
0.2
0.4
0.6
0.8
1.0

Figure 10

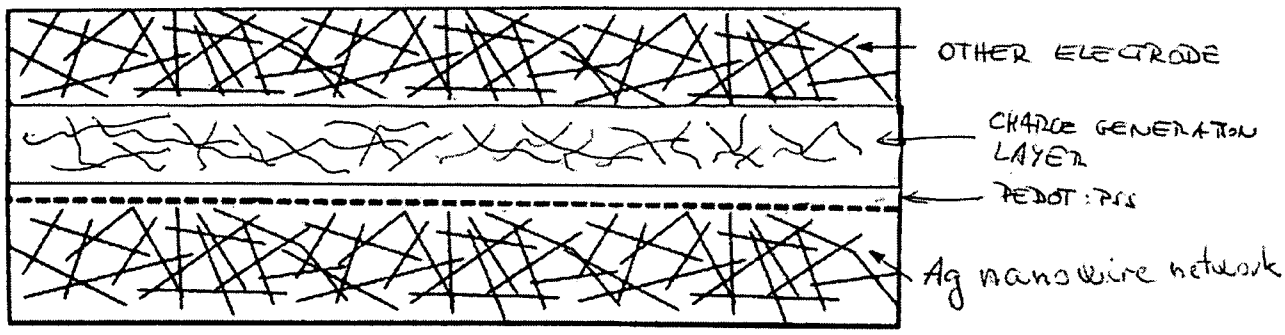


Fig 11.

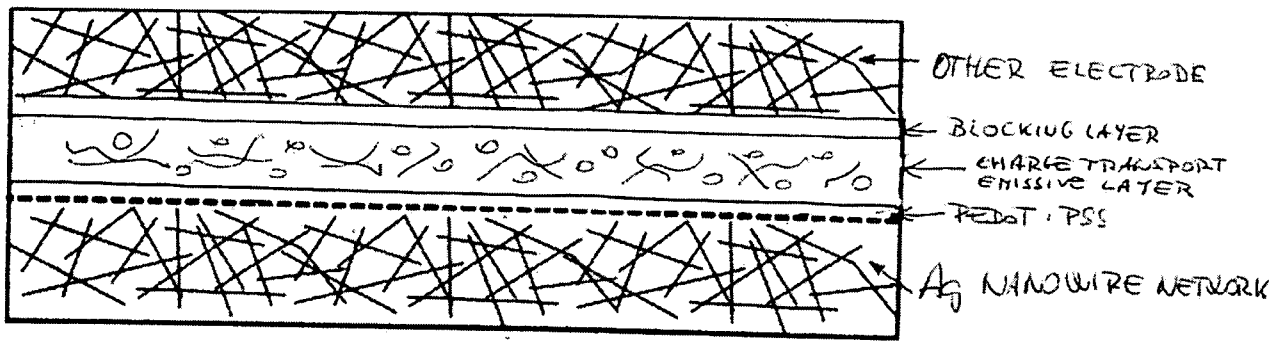


Fig 12.

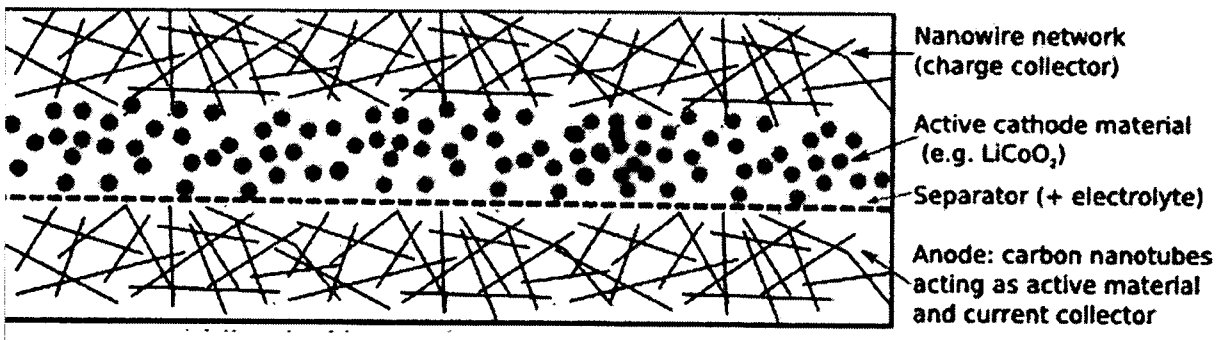


Fig 13