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Biocompatible carbon nanotube fibers for implantable supercapacitors

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ABSTRACT

The rapid advances in implantable electronic medical devices make supercapacitors highly desirable as power sources. These supercapacitors should be biocompatible, lightweight, miniature and stable without the need for packaging, which unfortunately remains unavailable yet. Here a new family of biocompatible carbon nanotube fibers were synthesized as electrodes to fabricate new supercapacitors that could directly work in physiological fluids including phosphate buffer saline, serum and blood with high energy storage capabilities. For instance, the specific capacitance reached 10.4 F/cm^3 or 20.8 F/g that could be maintained by 98.3% after 10,000 cycles in phosphate buffer saline.

1. Introduction

The rapid development of the flexible electronics opens up a variety of promising applications in biomedical fields such as monitoring biological signals including electrocardiogram, thermal, mechanical and electrophysiological information [1–3]. Among them, the appearance of implantable flexible electronic devices provides an efficient strategy to monitor health conditions inside the biological body [4–7]. To this end, it is critical to find matchable power systems that are supposed to be also biocompatible and implantable [8–10]. Supercapacitors with high power densities have been thus proposed as promising candidates to power the implantable electronic devices [11,12]. However, the conventional supercapacitors cannot well meet the above requirements. For instance, they are generally rigid and heavy, which is unsuitable for portable and flexible devices; the used electrolyte is unstable, so they need strict encapsulation, which makes surgery operations complex and the patients painful; the complex and rigid encapsulation also limits the miniaturization of the supercapacitors. One possible strategy is taking advantage of body fluid directly as electrolyte to avoid the encapsulation.

Carbon nanotube (CNT) materials, especially aligned CNT fibers, are recently studied for light weight, high flexibility, and excellent mechanical and electronic properties [13–16]. However, their hydrophobic nature has limited their applications in biomedical field. For instance, the anisotropic structure of aligned CNTs could be used to guide the growth and differentiation of cells in various tissues, but the poor interaction between hydrophobic CNTs and cells largely decreased cell attachment and growth rate [17,18]. Besides, their large specific surface areas and high electrical conductivities made them promising as electrodes in fabricating energy storage devices such as supercapacitors, but their poor wettability to the electrolyte that was typically hydrophilic led to a relatively low energy density [19].

Here we developed a neat and effective strategy to continuously

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synthesize biocompatible CNT fibers as effective electrodes for novel supercapacitors with physiological fluids including phosphate buffered saline (PBS), serum and blood directly acting as electrolytes (Fig. 1(a)). The specific capacitance reached 10.4 F/cm^3 or 20.8 F/g that could be maintained by 98.3% after 10,000 cycles.

2. Experimental section

2.1. Synthesis of hydrophilic aligned CNTs

Spinnable CNT arrays were grown in a tube furnace for 10–20 min by chemical vapor deposition, and they were then treated by an oxygen microwave plasma (Plasma System 690, PVA Tepla). The treated power was tuned from 50 to 200 W under a fixed time of 10 min with a pressure of 0.1 mbar and a flow rate of oxygen gas of 300 sccm. Hydrophilic CNT sheets were directly drawn from the modified CNT arrays, and the hydrophilic CNT fibers were prepared by the following twisting of the hydrophilic sheets at a rotary speed of 200 revolutions per minute. The CNT fibers were wound on a collecting drum with a speed of 15 cm per minute.

2.2. Cell culture and characterization

NIH-3T3 cells were cultured in Dulbecco's modification of Eagle's medium supplied with 10% fetal bovine serum, 100 U/ml penicillin and 0.1 mg/mL streptomycin. They were incubated at 37 °C in a humidified environment containing 5% CO_2, and the culture medium was changed every three days. The NIH-3T3 cells were fixed in a 4% paraformaldehyde solution in PBS solution for 5–10 min. Next, they were treated with 1% bovine serum albumin in PBS solution to block nonspecific binding sites for 30 min. After washing with PBS solution, the NIH-3T3 cells were stained with the phalloidin-fluorescein isothiocyanate and Hoechst 33342 to label F-action and cell nucleus. Finally, they were imaged by laser confocal scanning microscopy (LSM710, Carl Zeiss, Germany) and fluorescence microscopy (BX51, Olympus, Japan). NIH-3T3 cells were fixed at 2.5% glutaraldehyde in phosphate-buttered saline for 4 h at 4 °C. After washing with water for three times, they were dehydrated by 20% dimethylsulfoxide in water for 4 h and dried in critical point dryer, followed by coating platinum using a sputter coater. The samples were observed under a field emission scanning electron microscopy operated at 3.0 kV (Ultra 55, Carl Zeiss, Germany). Serum and blood came from mice (BALB/c, male, 6–7 weeks) that provided by Shanghai Laboratory Animal Centre and acclimatized under standard conditions, with a 12 h light/dark cycle.

3. Result and discussion

To synthesize biocompatible CNT fibers, spinnable CNT arrays were firstly synthesized by chemical vapor deposition [20], followed by oxygen plasma treatment (Fig. 1(b–d)). During the oxygen plasma treatment, atomic oxygen species, which were produced by breaking the binding energy of covalent bonds in

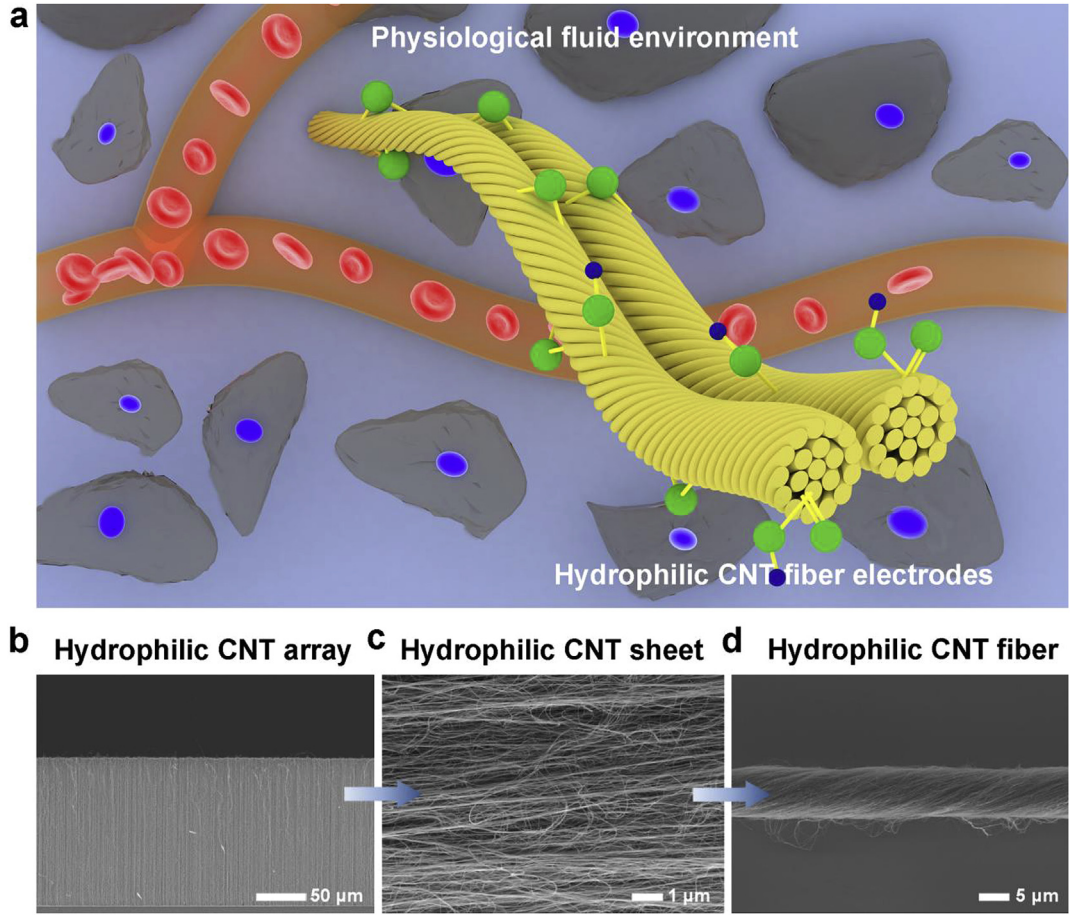

Fig. 1. Biocompatible supercapacitor in the physiological fluids. **(a)** Schematic illustration to the hydrophilic CNT fiber as two electrodes to fabricate fiber-shaped supercapacitor in the physiological fluids. **(b–d)** Photographs of spinnable hydrophilic CNT array, pulled CNT sheet and twisted CNT fiber, respectively. (A colour version of this figure can be viewed online.)