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Viewpoint Article

Electrical transport in carbon nanotube fibres

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ABSTRACT

Individual carbon nanotubes are highly interesting electrical conductors which could well complete with superconductors. Yet, the possibility of production of top-performance carbon nanotube electrical conductors beyond nanoscale, is the question currently challenging scientists.
This study discusses theoretical potential of macroscopic fibres made purely of carbon nanotubes, in charge transport and electrical applications. It also examines various aspects of their electrical conductivity including both direct and alternating current transport, weight-conductivity ratios, current density and doping issues. The reasons for the constraints in electrical transport in fibres manufactured today are explained, as are possible routes to achieving significant improvements in the performance.

1. Introduction

At the UK's Royal Society Science Summer Exhibition in London (2013), our research team demonstrated to the public that properly engineered carbon nanotubes (CNTs) may work as macroscopic electrical conductors in many electrical machines by replacing their copper windings with CNT wires (Fig. 1) [1,2]. This proper engineering starts with the spinning of CNT fibres, that is forming yarn-like assemblies of longitudinally aligned CNTs [3], combining many yarns together to form CNT cords and then coating the cords with standard insulating polymers [4]. Further steps of the process include cutting the wires to desired length, winding the chosen machine design and connecting electrically using a newly-developed carbon solder [5].

The device, which attracted the most attention at the Royal Society event, was a small DC generator in which the copper windings were fully replaced by CNT windings. Images of all parts of this generator are presented in Fig. 2 a). While Fig. 2 **b**) shows a magnified image of the rotor fully wound with CNT wires of approximately 0.5 mm diameter (with insulation). Each winding had 33 turns and a resistance of approximately 90 Ω. The operation of this device is presented in online Supplementary Materials (Video 1).

In testing the CNT wound generator it was found that it performed, in terms of the voltage generated at a specific angular velocity, as is predicted by conventional theories. Fig. 3, below, shows the experimental results recorded, in no-load conditions, of the maximum voltage produced at the output of the CNT wound generator, against increasing rotational velocity. In accordance with classical theory, the graph is linear and increasing.

Further tests showed that the power generated at the output of the tested device was enough to light a red diode (1.5 V, 2 mA). It was lit at approximately 3000 RPM (see also online Supplementary Video 1). However, this was close to the limit of operation for the device, which had a very poor performance in comparison to a copper wound version. Recently an independent group reported building an almost identical machine wound using fibres spun using a different fibre manufacturing process [6]. Elegant extensive modelling and experimental testing yielded exactly the same result. The reason for the poor performance of both devices was the high resistance of the CNT fibre based windings. Therefore, the key question is; Will CNT fibres ever be able to reach a sufficient conductivity to compete with copper?

2. DC electrical transport within the fibre

As theorized by Xu et al. fibres could in principle transport electricity almost like one, long, ballistic conductor [7]. "Almost" comes from the fact that they could be a true ballistic conductor only if the CNT fibres were made exclusively of long, single-walled CNTs of one armchair chirality, which would contact each other with a chirality dependent overlap of a precise length. As a precise length of overlap would seem to be technologically impractical to achieve, the authors calculated that it would be sufficient just to have a very long overlap. In this case, it is

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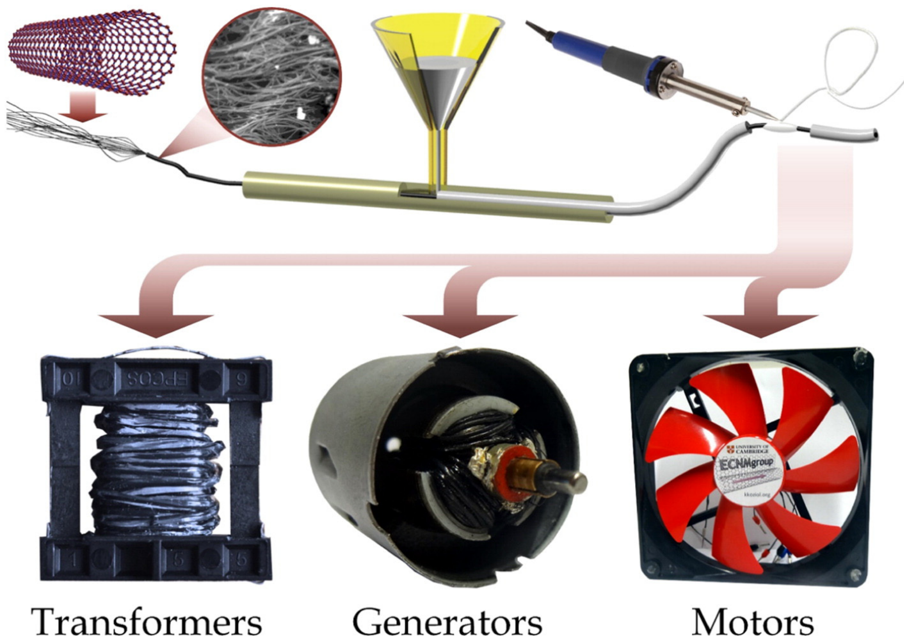

Fig. 1. The manufacture of carbon nanotube wires, which are then used as windings in electrical machines, such as transformers, generators and motors.

calculated, that a voltage of 0.04 V applied to the whole fibre would be sufficient to drive electrons freely [7].

However, when considering the conductivity of CNTs, it is important to remember that a ballistic conductor is not fully resistanceless. Each CNT connected to standard metal contact will theoretically experience a resistance of at least 6.5 kΩ, which equals half of a quantum resistance predicted for very narrow conductors [8]. So when considering a practical fibre of, for example, 10 μm diameter and made only of single walled armchair nanotubes of (10.10) chirality, we may calculate a theoretical limit of conductivity. Assuming a dense hexagonal packing of (10.10) nanotubes in a round cross-sectional area of 5 μm radius, the fibre will have approximately 31 million nanotubes that should be in direct contact with a metal contact pad. Hence the conductance of the fibre due to connections cannot be higher than approximately 4600 S which, in turn translates to theoretical values of 5.9×10^{11} S/m, 5.9×10^{13} S/m and 5.9×10^{16} S/m for a 1 cm, 1 m and 1 km long fibre, respectively (see online Supplementary Materials for calculation details).

Obviously for other chiralities these values will change as the number of nanotubes in a given cross-section depends on the diameter of the nanotubes. Calculations of conductivity performed for one length and dimeter of the wire but various armchair nanotubes show that the conductivity scales inversely proportionally to CNT diameter (Fig. 4 a)). Considering the fact, that not all armchair nanotubes will be practically useful as the (2.2) and (3.3) nanotubes were found stable only as inner walls of multi-walled CNTs [9,10] and nanotubes beyond (15.15) are prone to collapsing [11], we may show that e.g. for a 1 m long wire of 10 μm diameter the conductivities will vary from as much as 2.1×10^{14} S/m for (4.4) nanotubes to 3×10^{13} S/m for (15.15).

Thus, summing up all the energy losses expected from an ideal theoretical CNT fibre, we might expect it to be significantly better than any conventional metallic conductor.

However, this is conditional on the fibres having the ideal structure explained above. In our recent extensive review paper, we recognized a set of research challenges to overcome in current fibre manufacturing processes, so as to obtain these ultimate CNT conductors [3]. These include the simultaneous elimination of multi-walled CNTs and synthesis/use of longer nanotubes, the precise control of chirality, removal of impurities and defects and finally the ensuring of perfect alignment and densification of the fibres. However, it is just as important to consider the very practical aspects such as the length and diameter of

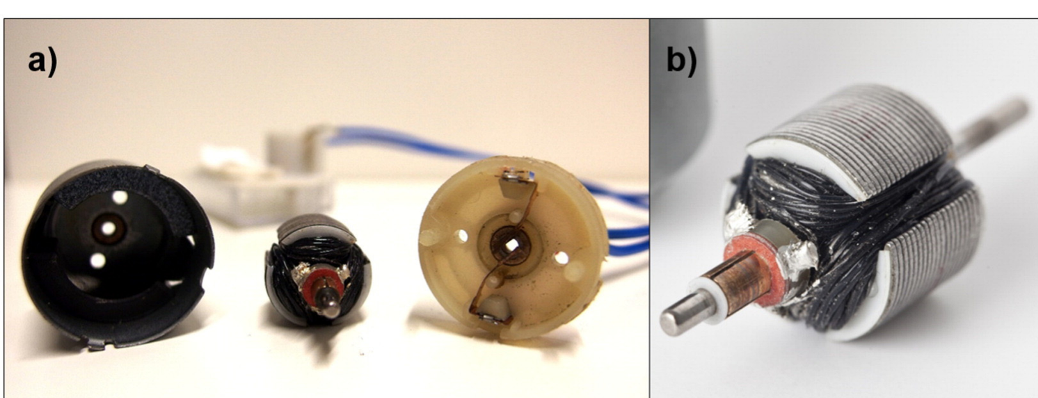

Fig. 2. a) Three main parts of the generator: stator (left) with two permanent magnets which accommodates the rotor (middle) with CNT windings and a plastic cap (right) with metal brushes and electrical terminals to connect the generator to external circuitry. b) A close up of the generator rotor with carbon nanotube windings.