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A critical review of experimental results on low temperature charge transport in carbon nanotubes based composites

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ABSTRACT

Owing to their low density, high aspect ratio and excellent charge transport properties, Carbon nanotubes (CNTs) are proven to be one of the best reinforcing materials in the fabrication of composite materials. CNTs dispersed in a non-conducting matrix is an interesting system for condensed matter physicists and materials scientists; CNT based composites offer an opportunity to physicists to design different experiments for fundamental studies while these composites are suitable for several technological applications that are of interest to materials scientists. In this review article, we summarize interesting experimental results on low temperature charge transport properties of composites based on multi-wall carbon nanotubes (MWCNTs) that have been reported in the past decade. In particular, we critically review different conduction mechanisms that have been identified through detailed investigations of charge transport characteristics as functions of MWCNT loading in the composites, temperature, and magnetic field.

Introduction

Carbon nanotubes (CNTs) exhibit a combination of exceptional mechanical and electrical properties that make them an important material for next generation technological applications to such areas as specific molecule detection of minute amounts, integrating basic components in the digital electronic systems, field emission displays, etc. [1–6]. Other than its technological significance, CNTs are quite fantastic one-dimensional molecular nanostructures for fundamental research, especially for the electronic transport studies owing to sp^2 hybridization of carbon atoms in a cylindrical honeycomb lattice. Electrical properties of CNTs have been widely studied in the last two decades [7–12]. It has been noticed that the charge transport in CNTs depends on a number of parameters including defects, doping of tubes, number of tube junctions, scattering centers, tube-tube interactions, number of walls, semiconducting/metallic nature, etc. These parameters play a major role in determining transport behavior that can vary from ballistic to diffusive. For an instance, room temperature (RT) resistivity for CNTs with a diameter of ~10 and 18 nm were estimated to be ~10 and 50 mΩ m, respectively [13,14]. Interestingly, at low temperatures an isolated CNT (with no defects) behaves like a one-dimensional quantum wire in which the electrons follow ballistic transport along the length of the wire (i.e. electrons travel without being scattered) [15]. This happens if the length of CNT (L) is small enough in comparison to the mean free path (L_m) and phase relaxation length (L_φ) of charge carrier. The mean free path is the distance which a carrier traverses between two consecutive scattering events.

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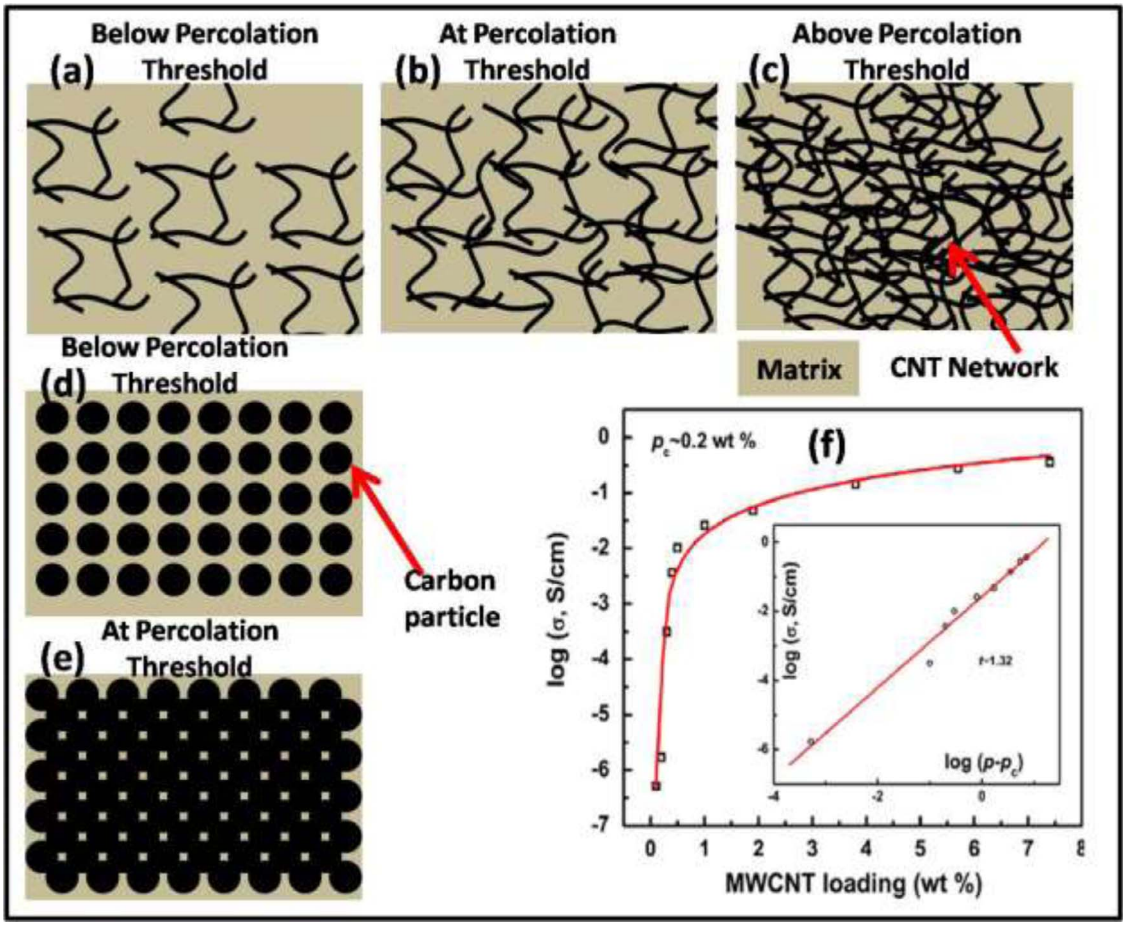

Fig. 1. Schematic illustration of electrical percolation in the case of (a-c) CNTs i.e. one dimensional material and (d-e) spherical carbon particles. Electrical percolation can be achieved at low wt fraction in CNT than in carbon particles. (f) Variation of dc electrical conductivity of MWCNT-PVC composites as a function of MWCNT loading (p). The dots represent the experimental points and the solid line is fit to$\sigma = \sigma_\circ (p - p_c)^t$. Electrical percolation at 0.2 wt.% of MWCNT is achieved. Inset. log σ vs. (p-p_c). The solid line is a linear fit to $\log\sigma = \log\sigma_\circ + t\log(p - p_c)$; the estimated value of the critical exponent t is 1.32. From ref. [21].

The distance over which the phase coherence is retained is called a phase relaxation length (or inelastic scattering length). This length scale is unaffected by elastic scatterings (scatterings where the scattering potential does not change the carrier energy but a phase shift occurs in the wavelength that is coherent). Further, when the length of CNT is larger than both phase coherence length and mean free path i.e. $L > \; > L_\phi > \; > L_m$, localization phenomenon is expected. In this case characteristic length scale is the localization length, L_c. Depending upon whether L_c is larger (smaller) than L_φ, the conductivity of the sample lies in weak (strong) localization regime. Another possibility can exist in which $L > \; > L_m > \; > L_\phi$, in this case classic transport is followed i.e. $R \propto L$ (Ohm's law). Other transport phenomena relevant to CNTs include universal conductance fluctuations, positive magneto conductance and wave function shrinkage in the presence of magnetic field. These can occur for samples in the localization regime. Bachtold et al. have also observed Aharnov-Bohm oscillations in the magneto conductivity of an isolated SWCNT under parallel field whereas hopping transport involving localization of carriers has been extensively reported in CNTs [8,16–19]. Positive magneto-conductance and wave function shrinkage have been reported for bulk forms of SWCNTs [17].

Further, CNTs are proved to be one of the most promising reinforcing materials owing to their low density and high aspect ratio. The inclusion of CNTs in polymer matrix in small quantities improves the mechanical, electrical and thermal properties [5,6]. We shall be considering only the improvement in the electrical properties of composites after the inclusion of CNTs. The room temperature electrical properties of CNT reinforced-polymer composites is governed by classical percolation theory [20], according to which the electrical conductivity of polymer composite depends on the content of the conducting filler material. The conductivity of the composite sample increases abruptly as the filler content just crosses a particular value p_c, called *percolation threshold* when the conductive path is established within the polymer matrix. The onset for establishing the conductive path is called *electrical percolation*. Apparently, the conductivity increases with further addition of filler material and saturates at high loading. The phenomenon of electrical percolation is explained using a schematic presentation in Fig. 1(a)–(e), which attempts to illustrate the importance of one dimensional nature of CNTs over spherical carbon particles in achieving low percolation threshold. A typical plot demonstrating the phenomenon of electrical percolation published by Vasanthkumar et al. [21] as presented in Fig. 1(f) that shows variation of room