

Transparent Thin Films of Multiwalled Carbon Nanotubes Self-Assembled on Polyamide 11 Nanofibers**

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Electrospun polyamide 11 (PA11) nanofiber films are used as a guide for the deposition of two-dimensional networks of multiwalled carbon nanotubes (MWNTs). This method allows for the manufacturing of transparent and electrically conductive thin films. It is demonstrated that the sheet resistance (R_s) and transmittance (T) decrease, as the films become thicker due to longer electrospinning times or larger fibers. The transmittance could be improved by fusing (melting) the fibers at moderate temperatures or impregnating the film with a resin, showing that light scattering rather than absorption by the MWNTs or the polymer was responsible for a low transmittance. As the number of MWNT deposition cycles increases, the R_s decreases with a constant transmittance. A fused 100 nm film obtained after 10 min of electrospinning of the 2 wt % PA11 solution shows $R_s = 154 \text{ k}\Omega \text{ sq}^{-1}$ and $T = 83\%$ after ten MWNT deposition cycles. A 95% transmittance was achieved after removing the polymer fibers by heating the glass plate in air ($R_s = 440 \text{ k}\Omega \text{ sq}^{-1}$ after five MWNT deposition cycles).

1. Introduction

Transparent and electrically conductive materials are required for numerous applications such as liquid crystal displays,^[1] light emitting diodes,^[2] transistors,^[3] actuators,^[4] sensors,^[5] organic solar cells,^[6] smart textiles,^[7] and heated windows. Currently, commercially available transparent electrodes use glass panels coated with indium tin oxide (ITO), which suffers from several drawbacks. They are obtained by vacuum and high temperature processing, which is not suitable for many polymer substrates such as polyethylene terephthalate (PET), which are often used for touch screen panels and flexible devices. Furthermore, ITO films are brittle and will crack under a 2% strain losing their conductivity. Therefore, they are not applicable where a combination of conductivity and flexibility is required (e.g., antistatic coatings on fabrics or

elastomers). Finally, the decreasing resources of crude indium induced a ten-fold price increase between 2003 and 2006,^[8] which may limit the use of ITO in large-volume applications.

Carbon nanotubes possess outstanding electrical and mechanical properties (flexibility),^[9] and conducting nanotube coatings can be produced at room temperature. Thin films manufactured from single-walled carbon nanotubes (SWNTs) show a sheet resistance in the range of $0.15\text{--}2 \text{ k}\Omega \text{ sq}^{-1}$ at 80% transmittance.^[3,10,11] In comparison, ITO coatings possess a sheet resistance of about $10 \Omega \text{ sq}^{-1}$.^[3] Therefore, SWNT films may replace ITO in many devices. However, they possess a similar limitation as ITO — a high cost. It is difficult to expect the use of SWNTs for coating window glass, making antistatic fabrics, or producing conducting plastic panels for spray painting in the foreseeable future. Multi-walled carbon nanotubes (MWNTs) constitute an attractive alternative because they are much more affordable (the cost is 2–3 orders of magnitude lower as compared to SWNTs) and are produced in large volumes. Despite their higher resistance (2–3 orders of magnitude higher than SWNTs), which yields thin films of $\geq 250 \text{ k}\Omega \text{ sq}^{-1}$ at 80% transmittance,^[12,13] the implementation of MWNTs thin films remains very attractive in terms of cost/performance ratio, especially when considering short term and large volume commercialization. Unfortunately, only a limited effort has been dedicated to investigating conductive and transparent MWNT coatings.

Given the nanotubes tendency to form bundles, the manufacturing of uniform thin films has remained a challenge for both single- and multi-walled nanotubes. Generally, the nanotubes are dispersed in a solvent with the help of a surfactant. A film is then produced by spin-coating,^[13] spraying,^[3,7,14] rod-assisted coating,^[1,15] casting^[12,16], or filtration^[2,5,17] of the solution. However, the surfactant adsorbed on the surface of

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