



Nanotube Networks as Transparent Electrodes for Solar Cells

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Background

Low-cost flexible solar cells

Very low-cost thin-film flexible solar cells manufactured with roll-to-roll coating have the potential to help make solar energy a cost-competitive energy source. We have identified one specific part of thin-film solar cells where improvements are needed—that of the transparent conductor. We are working to investigate whether carbon nanotube (CNT) films can be made into transparent conductors that are compatible with low-temperature, ambient pressure, and ultimately low-cost based solar cell production techniques.

Cleanroom + High-T + Vacuum



Most current commercial solar cells are relatively rigid, bulky, heavy, and fragile and are manufactured in clean rooms using high temperatures and vacuum processes

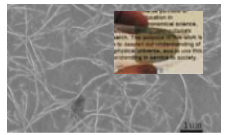
Solution Processing, Printable



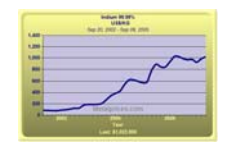
New approach: use thin film technology to achieve flexible, light-weight, rugged cells that can be fabricated using low-cost reel to reel coating techniques at low-T and in ambient pressure

A New Thin-Film Compatible Transparent Conductor: CNT-Networks

A critical element of most thin film solar cells is the transparent electrode layer. This layer must transmit light while simultaneously providing a low-resistance path for electrical current to flow out of the solar cell. The current material of choice for organic thin-film solar cells is indium-tin-oxide (ITO), a material with many shortcomings. CNT-films could replace ITO.



thin CNT Films have shown strong promise in the past year as transparent conductors



ITO Prices have risen due to scarce supply and exploding demand from the flat panel display market, while CNT prices are continuing to drop.

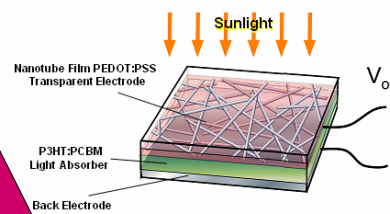
- CNT films**
 - Solution processable
 - Abundant raw materials
 - Highly flexible
 - Excellent stiction
 - Material ~\$0.75/m² and falling

- ITO**
 - high-quality ITO must be sputtered, annealed.
 - Indium is scarce, expensive (good ITO ~\$100/m²)
 - Relatively brittle
 - Delamination problems
 - Material ~\$1.00/m² and rising

Polymer/fullerene bulk heterojunction solar cell demonstrating CNT electrodes

M.W. Rowell, et al. App Phys Lett. 88, 233506 (2006)

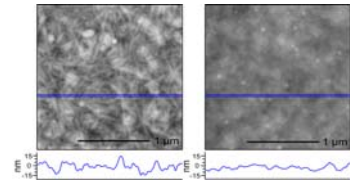
Solar cell utilizing CNT-film



We have fabricated flexible organic solar cells using both commercial ITO on glass substrates and CNT films from Prof. Gruner's lab in UCLA.

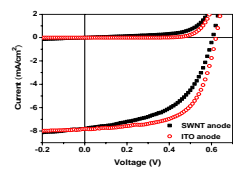
- small cells incorporating CNT films worked almost as well as ITO-based cells
- demonstrated shorting from nanotubes could be overcome through addition of PEDOT:PSS
- showed work function of nanotubes was compatible with P3HT/PCBM blend cell (current leading organic solar cell)
- verified that no contact resistance problems between active region and nanotubes existed

Conducting Polymer + CNT-film



AFM topographical images of printed CNT films a) bare and b) after spin coating with conductive polymer, PEDOT:PSS. Addition of PEDOT:PSS smoothed nanotube film and lowered resistance by 20% from 200Ω/□ to 160Ω/□.

CNT-film cells perform similarly to ITO based cells



I-V curves of CNT film solar cell and ITO test cell in dark and under illumination

PET / ITO / PEDOT:PSS / P3HT:PCBM / Al
J_{sc} = 8.0 mA/cm² V_{oc} = 610mV FF = 0.61

Efficiency = 3.0%

PET / CNT-film / PEDOT:PSS / P3HT:PCBM / Al
J_{sc} = 7.8 mA/cm² V_{oc} = 605mV FF = 0.52

Efficiency = 2.5%

CNT-Films: Rugged and flexible



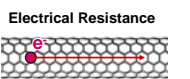
ITO on PET: Cracks Form at r_{bend}=5mm



CNT based solar cells could be flexed to beyond 5mm radius of curvature with no ill effects, while ITO based cells splintered at these flexing angles.

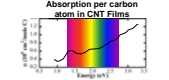
Scanning Probe Microscopy of CNT electrodes

CNT-Film Theoretical Performance



Due to their 1-dimensional nature and near perfect crystallinity, CNTs possess very long electronic mean free paths at room-T, (~1.6 microns¹ vs. ~20 nm in Cu). This results in extremely high conductivities-4nΩ m for 5-5 armchair tubes, (about 5 times better than Cu).

Optical Transmission



The optical absorption of nanotubes has been measured², and is roughly 98.5% transmission for each layer of nanotubes. This means that roughly 7 layers of nanotubes gives 90% transparency.

Theoretical Limit: 0.5Ω/□
90% Transmission

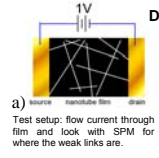
Current films: 200Ω/□
85% Transmission

Current CNT-film performance sufficient for small, lab-demonstration cells, but performance breakthroughs towards theoretical limits still needed to enable very low-cost thin-film cells

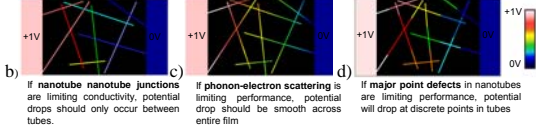
Use information from SPM studies to move CNT-Films toward theoretical performance limits

It is difficult to know from standard electrical resistance measurements what is holding CNT-film performance back.

Scanned probe microscopy (SPM) allows us to add spatial information to our understanding of the performance of these CNT-films...

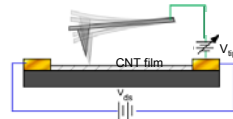


Different images indicate different underlying bottlenecks to performance...



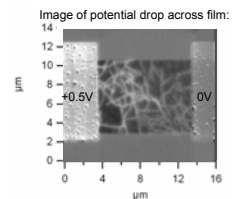
Electric Force Microscopy on CNT-Films

EFM, Electrostatic Force Microscopy, allows the mapping of electrostatic force or potential in a solar cell.



By flowing a current through the nanotube network and imaging where the potential drops, the bottlenecks in CNT-film performance can be directly, spatially imaged, hopefully suggesting possible paths to improved performance

First Round of SPM Results



An EFM image on a carbon nanotube film showing the potential drop across the film (from the left to right), and the tip was held at +3V with respect to ground and scanned 100nm above the surface of the film.

Certain Tube-Tube Junctions = Weak Link?

Bottleneck in CNT-film performance seems to be in tube-tube junction (option "b" above). Interestingly, there seem to be a series of critical junctions that are worse than any other junctions.

Conclusions & future work

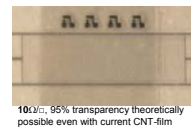
- Demonstrated CNT-Film Electrodes in organic solar cells
- Developed SPM imaging setup and technique, and performed preliminary measurements on test films
- Found surprising answer to question of what limits CNT-film performance: a series of critical high-resistance tube-tube junctions

Future Work

Continue SPM of CNT-films, investigate effects of addition of conducting polymers, doping of semiconducting nanotubes

- Are there ways to target and improve these "weak links" in the network?
- Can ways be found to get around these weak links (e.g. addition of conductive polymer or strengthening with metallic grid)?
- Demonstrate high-efficiency all-solution processed solar cell.

Reinforcement of CNT-films with sparse metallic grid



10x/□, 95% transparency theoretically possible even with current CNT-film

Acknowledgements

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¹J.Y.Park, et al Nanotechnology 4, 517 (2004) ²M.F. Islam, et al PRL 93, 037404-1 (2004), M.Zhang, et al. Science 309 (2005)