

Nanotube Networks as Transparent Electrodes for Solar Cells One Year Exploratory Research Grant

Investigators

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Introduction

This exploratory research project is aimed at investigating the use of a newly discovered electronic material, random carbon nanotube network (CNT) films[1, 2] for applications as transparent conductors in solar cells. Compared to existing transparent conductor technologies such as Indium Tin Oxide (ITO), CNT films have a number of potential advantages. These include the use of an abundant material (carbon), high film flexibility, and solution processibility. The gap between theoretical and real-world performance in terms of sheet resistance (R_s) and optical transparency (T) is probably still too large to allow current CNT films to be incorporated into commercial solar cells. In this project we are investigating what can be done to improve the performance of CNT films and to allow their incorporation into next generation solar cells.

Background

Carbon nanotube films have emerged as an active and rapidly advancing area of research. Recent work has been focused on a number of potential applications for solution-processible transparent conducting CNT films. In addition to the research aimed purely at improving film performance[3], recent work has demonstrated advances in using CNT films in a wide variety of applications – for instance, transparent transistors[4], antistatic coatings[5], gas sensors[6], pH sensors[7], and solar cell electrodes[8].

Prof. George Gruner's lab at UCLA, who we are currently collaborating with on the this project, recently detailed a new method of printing the films which combines the high quality attainable from vacuum filtration processes with the potentially low-cost patterning technique of PDMS stamp transfer[3].

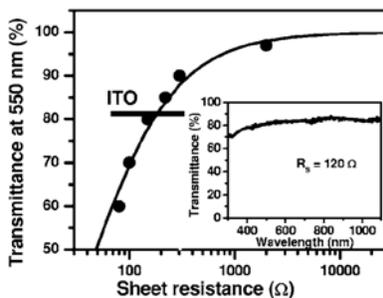


Figure 1: Graph showing transparency vs. sheet resistance for vacuum filtration produced, PDMS stamp transferred films

These films can now be produced using a solution-based process with higher conductivity ($120\Omega/\text{square}$) and higher transparency (85%) than was previously possible. We have used films similar to these in our research (see Results section below). Note that even with these improvements, the transparency and conductivity are both still over two orders of magnitude below theoretically achievable levels – research into better theoretical understanding and performance improvements is crucial.

Recently the use of single-walled carbon nanotube (SWNT) films as the transparent anode in a solar cell has been demonstrated on glass substrates.[9] Transparency of their CNT films, T , was low ($\sim 45\%$ for R_s of $282\Omega/\square$) and the device configuration was suboptimal, using an active absorber layer 800 nm thick—much thicker than is necessary to efficiently absorb sunlight.[10]. The performance of the resulting cells was significantly below efficiencies achieved in similar cells on ITO demonstrated elsewhere, and no tests of flexibility were possible due to the use of a glass substrate.

Results

We have completed the first stage of our research and have a manuscript in press based on this work. We demonstrated the use of CNT films as the transparent electrode for efficient, flexible polymer-fullerene bulk heterojunction solar cells. Solar cells using P3HT/PCBM in a process previously optimized for ITO coated glass were fabricated on the SWNT anodes without alteration. The achieved efficiencies, up to 2.5 % (AM1.5G), are very close to those achieved with ITO on glass and are affected primarily by R_s , the sheet resistance, of the carbon nanotube film. Bending test comparisons between solar cells on SWNT/plastic and ITO/plastic show the SWNT electrodes to be far more flexible.

CNT Film Preparation and Characterization

In order to construct our CNT film based solar cells, we started with a 30-nm thick SWNT network films on top of 125- μm -thick PET flexible substrates (see Figure 2).

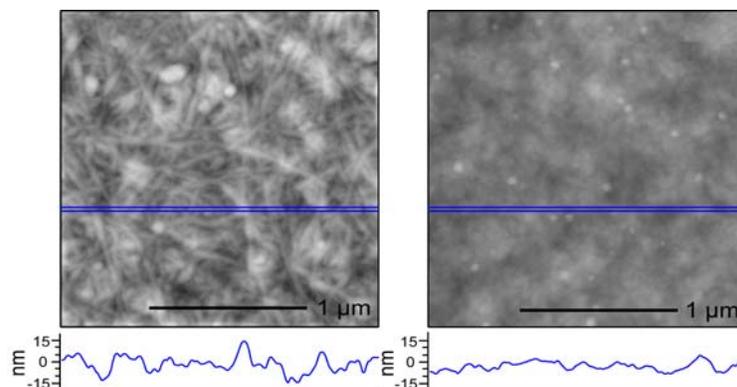


Figure 2. AFM images of SWNT network films used in the solar cells (a) before and (b) after PEDOT:PSS deposition and annealing at $110\text{ }^\circ\text{C}$ for 20 minutes. The RMS roughness is 7 nm before coating and 3.5 nm after coating.

These films were prepared in Prof. George Gruner's lab at UCLA using a combined vacuum filtration and PDMS stamp process[3].

Prior to depositing the active layer, a layer of PEDOT:PSS was spin-cast on the SWNT films (shown in Fig 2(b)). Interestingly, the PEDOT:PSS reduced R_s of the film by more than expected- approximately 20% to $160 \Omega/\square$. The PEDOT:PSS film by itself had a sheet resistance of about $15 \text{ k}\Omega/\square$, which would only be expected to lower the overall resistance of the PEDOT+CNT film to about $197 \Omega/\square$ if the PEDOT were simply functioning as a conducting layer in parallel with the CNT film. We theorize that the additional decrease in resistance is likely due to a reduction in the resistance between conducting nanotubes or partial doping of any semiconducting nanotubes. We hope to further investigate this effect using scanned probe techniques in the near future. Fig. 2(b) shows the SWNT films after being coated with PEDOT:PSS and the resulting low roughness. The addition of the PEDOT layer not only improved the conductivity of the CNT film, it also helped to remove problems with shorting we had due to outlying nanotubes sticking up from the film which would connect the CNT film to the Al electrode on the top of the cells.

Solar Cell Fabrication

After the addition of PEDOT to the CNT films, samples were then transferred to an inert glove box where a solution of P3HT/PCBM[11] in a 1:0.8 weight ratio (10 mg P3HT/mL) in chlorobenzene was spin-cast at 700 rpm. Finally, a 100 nm Al top electrode was evaporated under high vacuum at a rate of 0.5-0.1 nm/s. P3HT devices were annealed on a 120 °C hotplate for 10 minutes and had a post annealed optical density of 0.5. The overlap of the top and bottom electrodes defined a device 1 mm x 4 mm. The results are summarized in Table 1 for the flexible devices as well as a control device on ITO coated glass ($15 \Omega/\square$). The measured open circuit voltages (V_{oc}) suggests that, as proposed by *Frohne et al.*, [12] the V_{oc} is driven by the work function of the PEDOT:PSS layer rather than by the carbon nanotubes. Fig. 3 shows the current voltage curves for P3HT/PCBM cells under simulated AM1.5G conditions. Table 1 summarizes the performance of the P3HT on CNT coated PET vs P3HT on ITO coated glass.

Device Structure	j_{sc} (mA/cm^2)	V_{oc} (mV)	Fill Factor	Effic. (%)
PET / SWNTs / PEDOT:PSS / P3HT:PCBM / Al	7.8	605	0.52	2.5
Glass / ITO / PEDOT:PSS / P3HT:PCBM / Al	8.0	610	0.61	3.0

Table 1: Device metrics for CNT-film/PET and ITO/glass solar cells

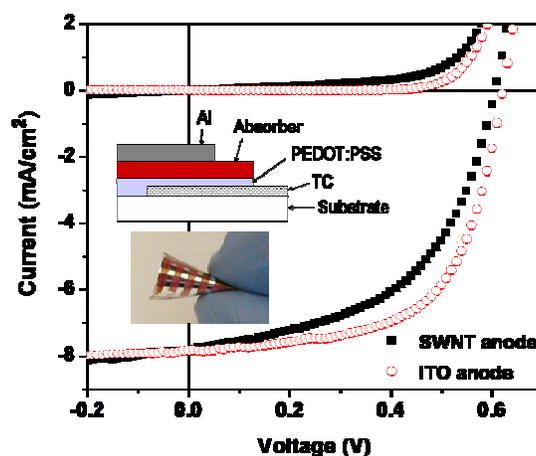


Figure 3: Current density-voltage characteristics of P3HT:PCBM devices under AM 1.5G conditions using ITO on glass (open circles) and flexible SWNTs on PET (solid squares) as the anodes, respectively. Inset: schematic of device and photograph of the highly flexible cell using SWNTs on PET.

As can be seen from Figure 3 as well as Table 1, the device results using SWNT networks operate similarly to those for ITO coated glass with the exception of the fill factor (FF), which is likely attributable to the high series resistance due to R_s , the sheet resistance of the CNT film

Solar Cell Flexibility

The stability of devices fabricated on the SWNT/PET films was much greater than devices on ITO/PET during simple bending tests. SWNT devices could be folded over (inducing compressive or tensile strain) down to radii of curvature of ~ 5 mm with no degradation in power efficiency and radii of ~ 1 mm with a 20-25 % loss in efficiency. However, annealing for 5 minutes at 130 °C completely restored the efficiency in 2 out of 3 tests. The mechanisms involved in the failure or the restoration have not been investigated. In comparison, devices using ITO ($R_s = 40 \Omega/\square$) on the same $125\text{-}\mu\text{m}$ -thick PET substrate began to fail at a radius of 1 cm and completely failed at 5 mm with fractures in the ITO visible to the eye.

Progress and Future Directions

We have demonstrated the possibility of using carbon nanotube films in an organic solar cell which is potentially compatible with solution-based reel-to-reel processing, and are currently engaged in investigating whether the fundamental performance of these CNT films can be significantly improved. The replacement of relatively expensive,

brittle transparent conductors currently used in solar cells (such as Indium Tin Oxide, ITO) could help to pave the way for more cost effective, grid-competitive solar cell technology. The impact of grid-competitive solar cell technology on greenhouse gas emission would be significant - electricity generation consumed 34 percent of U.S. energy from fossil fuels and emitted 40 percent of the CO₂ from fossil fuel combustion in 2004.[13]

The next step in our research program is to take the existing carbon nanotube films and work at improving their performance to levels where they will no longer adversely affect the performance of the resulting solar cells. We are currently preparing to investigate the performance of these films using a variety of scanned probe microscopy techniques, including electric force microscopy (EFM) and scanned conductance microscopy, as well as some previously untried techniques such as scanned tapping mode potentiometry. The effects of partial tube alignment, the addition of conductive polymer (PEDOT), and the possible chemical doping of the nanotubes (to turn semiconducting tubes metallic) will be investigated both with transport measurements and scanning microscopy techniques.

Publications and Conference Presentations

1. "Nanostructured Hybrid Organic-Inorganic Photovoltaic Cells," M.D. McGehee, Materials Research Society Meeting, San Francisco, CA, April 17-21, 2006.
2. "Carbon Nanotube Films as Flexible Transparent Conductors for Solar Cells", M.A.Topinka, M.W.Rowell, M.D.McGehee, L.Hu, D.Hecht, G.Gruner, American Physical Society March Meeting, Baltimore, MD, March 13-16, 2006.
3. "Organic solar cells with carbon nanotube network electrodes," M.W. Rowell, M.A. Topinka, M.D. McGehee, H.J. Prall, G. Dennler, N.S. Sariciftci, L. Hu, G. Gruner, *Applied Physics Letters* (in press).

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13. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004, (April 2006), USEPA #430-R-06-002

Contacts

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