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From the Editors of R&D Magazine

CONTENTS

Nanotechnology

Green carbon nanotubes

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For centuries, carbon has been synonymous with black. Then, discoveries in the 1990s showed that carbon can be transparent. Now, it is green. Carbon in the form of carbon nanotubes (CNTs) is becoming a popular material for renewable energy, enabling technologies from hydrogen fuel cells to solar cells. Single-walled carbon nanotubes (SWNTs) are useful as a transparent conducting electrode in photovoltaics (PVs), replacing indium tin oxide (ITO) and zinc oxide (ZnO) with the benefit of lower process cost and greater mechanical flexibility.

A special member of the nanotube family is the SWNT, which consists of one rolled

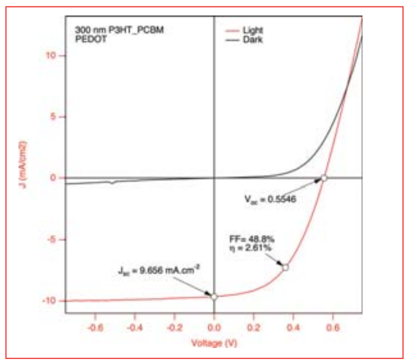

Fig. 1. Current voltage curve of organic PV with SWNT electrode. *Source for all graphics: Eikos Inc., Franklin, Mass.*

continued on page 6

BUSINESS NEWS

EpiCrystals, Tampere, Finland, won the European Venture competition as the best venture from among 18 finalists. The company uses molecular beam epitaxy methods to create GaAs- and InP-based laser diodes.

Reiner Peters from NASCO-MED (www.nascomed.de), Germany, has coined the phrase nanoscopic medicine—a new nanotech discipline that analyzes/improves the nanoscopic fundament of the cell.

Ill.-based **AMCOL** (www.amcol.com) has devised a nanocomposite for plastic beer bottles that keeps oxygen molecules out and CO_2 molecules in.

Green carbon nanotubes
continued from page 1

graphitic sheet ~1-nm dia. The physical structure of SWNTs makes them ideal for creating a 2-D network of nanowires which, due to high volume conductivity, is as conductive as ITO or ZnO at film thicknesses <100 nm. The physical, chemical, and electrical properties of CNTs make them suitable for green technology applications.

PVs are a well-known and prominent green technology. Industry and government initiatives in solar production are expected to grow the market 40%/year, from 2 GW of production in 2006 to almost 10 GW in 2010. Crystalline Si cells make up a majority of this market, but non-traditional technologies such as copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), dye sensitized, and organic polymer solar cells will outpace overall growth, expanding from 0.15 GW to 2 GW in the same time frame. These designs utilize roll-to-roll manufacturing methods and produce cells at a lower cost/watt. The ideal transparent conductor (TC) for these designs is mechanically flexible and can be applied in ambient conditions using wet-process equipment.

Making SWNT solar cells

SWNTs are ideal TCs for solar cell applications. Eikos has formulated a brand of Invisicon inks that are liquid dispersions of purified and functionalized SWNTs. These inks are applied using a variety of methods including slot-die coating, gravure coating and inkjet printing. Van der Waals forces pull together dispersed nanotubes as the ink solvent dries, assembling the nanotubes into a thin, uniform, conductive network. These open-pore networks can be made at a broad range of sheet resistance (1-10^7 ohm/sq) and can be infiltrated with a polymer to make flexible, mechanically robust films.

Five different solar cell designs were fabricated using spray applied transparent SWNT electrodes (Table 1, below), which represent a diverse selection of non-traditional thin film and novel PVs. They were fabricated in collaboration with the National Renewable Energy Laboratory (NREL), Golden, Colo., and leading solar companies. For most cell types, SWNT sheet resistance ranged from 50-200 ohm/sq with a transparency of 70%-92%, respectively. Though not fully optimized, these processes yielded cells with efficiencies on par with control devices made with standard TCs. For processing and technical reasons, the most promising devices are organic photovoltaics (OPVs) cells. With SWNT electrodes, they are true organic, green energy sources.

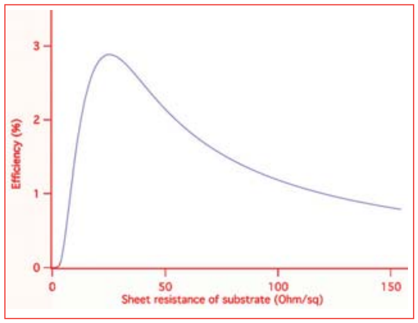

Fig. 2. Modeled efficiency vs sheet resistance for SWNT enabled OPV.

Fully organic PVs

Despite lower efficiencies, OPVs are being developed for their low-cost manufacturing. SWNT electrodes are ideal for this device type with a 4.9 eV work function and p-type conduction. Two OPV constructions were fabricated with NREL (Table 1). A maximum efficiency of 2.61% was achieved when ITO was replaced with an SWNT electrode. This device was spray coated on microscope glass to 50 ohm/sq with an associated transmittance of 70% at 650 nm. Poly3,4-ethylenedioxythiophene polystyrenesulfonate (PEDOT:PSS) was spun on and thick (0.5-1 µm) films of poly-3-hexylthiophene (P3HT) and [6,6]-phenyl C61 butyric acid methylester (PCBM) 1:1 were drop cast on top and allowed to slowly dry for 30 min in an argon (Ar)-atmosphere glove box. Aluminum (Al) top contacts (~100 nm) were then deposited onto the device by thermal or e-beam evaporation. Finally, the devices were annealed at 120°C for 30 min in the glove box. The current density-voltage (J-V) curve of this 2.61% efficiency device is shown in Fig. 1 (page 1). Except for the Al contacts, the replacement of inorganic ITO with SWNT electrodes yields an OPV device.

The OPV in Fig. 1 can be optimized further. Samples were made at 50, 75, 100, and 150 ohm/sq SWNT sheet resistance with a trend that lower resistance values (more nanotubes) allow more current to flow, creating higher solar conversion efficiency. This trend continues until very low sheet resistance occurs as additional layers of SWNTs decrease transparency, which lower photo induced current and efficiency. This trade off is modeled in Fig. 2 (left) with a maximum efficiency of nearly 3% at an optimal SWNT sheet resistance of ~25 ohm/sq. To lower OPV cost further, fewer polymer layers can be used. Table 1 shows an efficiency of 1.43% for an organic device with SWNT and Al electrodes sandwiching the P3HT:PCBM active material, replacing ITO and PEDOT: PSS in the reference device. ITO electrodes will not function in these devices because of their n-type conductivity. Though the efficiency is lower for this device, its simple construction could be useful for low-cost, recyclable PVs.

Green future

SWNT transparent electrodes have comparable performance to ITO and ZnO electrodes while offering the benefit of solution processing and mechanical flexibility. These factors are critical in the new generation of thin film and novel renewable solar energy technologies, which are manufactured in low cost roll-to-roll processes. Due to work function matching and p-type conduction, these electrodes are suited to OPVs and can create a fully organic device. The CNTs are produced from renewable materials. Ethanol, a carbon source for producing quality nanotubes, is generated in volume from plant sources, making it an ideal renewable precursor for green nanotubes. SWNTs are used by Eikos to produce Invisicon transparent conductive coatings for applications ranging from solar cells to LCD displays and touch screens. At the end of product lifetime, nanotube coatings can be recycled or incinerated to their carbon and hydrogen components.

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Paul Glatkowski (pglatkowski@eikos.com) is VP of Engineering at Eikos and the inventor of CNT Invisicon transparent conductive coatings.

David Britz (dbritz@eikos.com) is a Sr. Engineer at Eikos and has seven patents pending relating to CNT composites, film, and apps.

Five different solar cell designs

Cell	Name	Structure	Efficiency, SWNT TC	Efficiency, control TC
OPV	Organic photovoltaic	SWNT/PEDOT:PSS/ P3HT:PCBM/Al	2.61%	~3%
OPV	Organic photovoltaic	SWNT/P3HT:PCBM/Al	1.43%	N/A
DSSC	Dye sensitized solar cell	Ti/TiO_2/dye/SWNT	2.86%	2.20%
CIGS	Copper indium gallium diselenide	SWNT/i-ZnO/CdS/CIGS/Mo	12.98%	~15%
Tandem	Cadmium telluride top cell	ITO/CdS/CdTe/CuTe/SWNT	12.4%	12.9%

Table 1. For variety of cells, SWNT conductors offer benefits at similar efficiencies.