Carbon-Nanotube Transparent Electrodes for Flexible Displays

The search for the ideal transparent electrode for flexible displays in lieu of the brittle and expensive indium tin oxide (ITO) electrode continues. Single-wall carbon-nanotube (SWNT) coatings, especially on plastic films, are a viable alternative to ITO for flexible-display applications, offering superior durability and flexibility, ease of processing (wet coating and patterning), low reflectance, and neutral color.

by J. Peltola, C. Weeks, I. A. Levitsky, D. A. Britz, P. Glatkowski, M. Trottier, and T. Huang

THE development and commercialization of flexible-display technologies has gained substantial momentum and will experience double-digit growth rates within the next 5 years. The transformation of rigid, glass-based display concepts to flexible, lightweight, and bendable structures requires innovation not only in the development of new materials, but also in substrate handling and process technologies.

One of the challenges facing developers of flexible-display technology is the need for low-cost durable transparent electrodes. Coventional transparent conductive materials include semiconducting metal oxides, such as indium tin oxide (ITO), and, to a lesser degree, conducting polymers. ITO is inherently brittle, whereas conducting polymers demonstrate undesirable optical transmittance over the visible region. Recently, alternate conductors based on single-wall carbon nanotubes (SWNTs) that overcome many of the shortcomings of both ITO and polymer conductors have emerged.

SWNT-Film Characteristics

Most display technologies require one or more transparent electrode layers. ITO has been the transparent conductor of choice due to its optoelectronic performance and lack of alternatives, but exhibits certain drawbacks: It is costly to manufacture and pattern, and has a tendency to crack with use due to its low modulus. The newest transparent conductor material based on SWNT delivers low-cost flexible alternatives. SWNT films and coatings exhibit many advantageous properties as listed in Table 1.

SWNT films enable flexible-display designers to create high-performance low-cost devices with fully flexible form factors. SWNT coatings can be fabricated at low temperature on any substrate, facilitating the use of roll-to-roll manufacturing, thus reducing fabrication time, equipment cost, and reject rate.

SWNT-Film Morphology

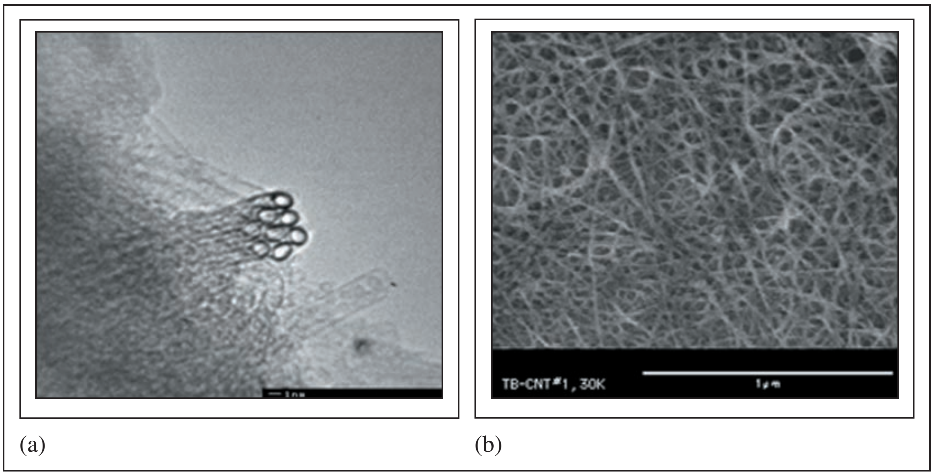
SWNTs are an allotrope of carbon formed in the presence of carbon, heat, and a metal catalyst and are typically 1–2 nm in diameter and several microns long. They have strong bonding and show an affinity to bundle or "rope" during processing. High-purity and high-yield dispersions of SWNT can be produced from raw materials. When a carbon-nanotube

Table 1: Advantageous properties of SWNT films and coatings

- Broad surface resistance (10-107 Ω/_.)
- Optical transmittance >90%
- Work function 4.8 eV
- P-type conductor
- Uniform and linear conductance
- Thin-film technology (10 – 100 nm)
- Low reflectivity
- Neutral color tone
- Adhesion
- Durability
- Good chemical resistance
- Flexibility
- Patterning capability
- Wet-processing
- Scalable process

***J. Peltola, C. Weeks, I. A. Levitsky, D. A. Britz, P. Glatkowski, M. Trottier**, and* ***T. Huang** are with Eikos, Inc., 2 Master Dr., Franklin, MA 02038-3034; telephone 508/528-0300, fax -0101, e-mail: jpeltola@eikos.com.*

0362-0972/02/2007-0??$1.00 + .00 © SID 2007



(a) (b)

Fig. 1: SWNT morphology. (a) TEM image of SWNT ropes. (b) SEM micrograph of SWNT film with a surface resistance of 100 Ω/sq.

(CNT) dispersion is deposited onto a substrate (glass, plastic, paper, or metal), it forms a conductive 2-D network as the solvent evaporates and allows the ropes to assemble. Transmission (TEM) and scanning electron microscope (SEM) micrographs of the SWNT networks are shown in Fig. 1.

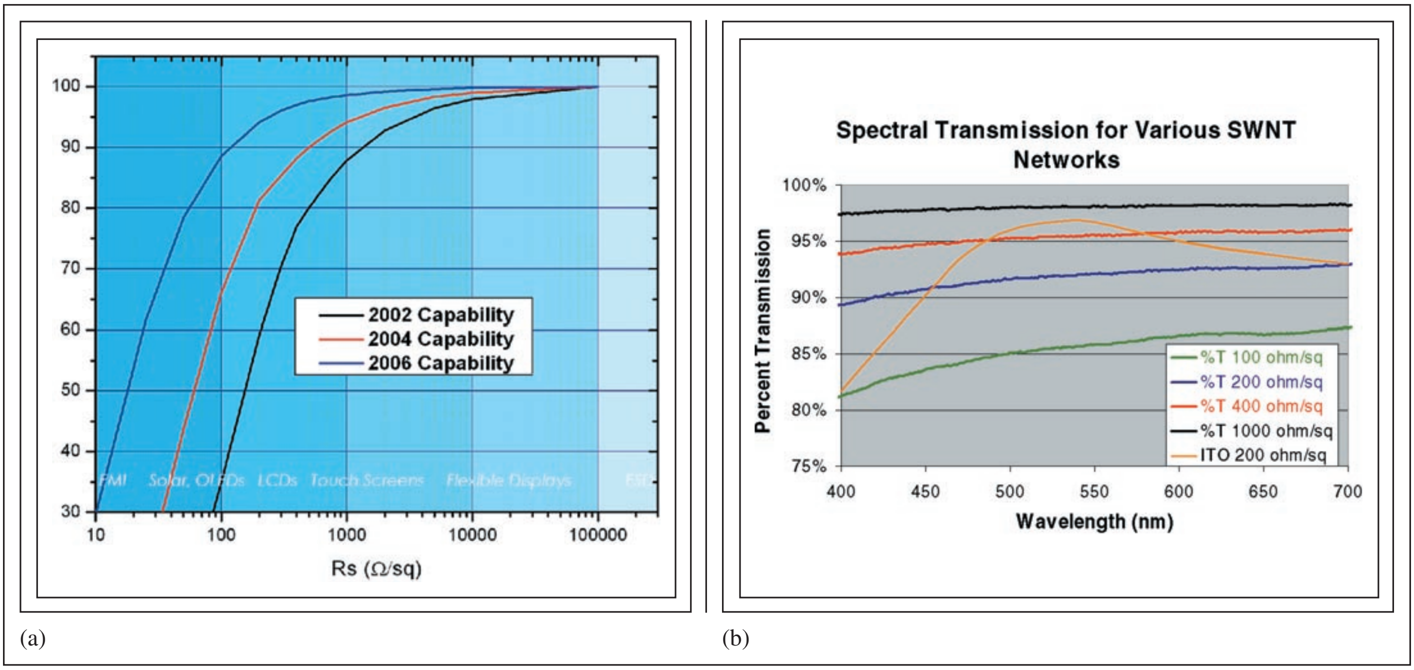
SWNT Optoelectronic Performance

The optoelectronic performance of these SWNT coatings is continuously improving as its chemical and physical characteristics are optimized to increase conductivity while reducing the layer thickness. An obvious advantage of the SWNT coatings is the ability to tailor the sheet resistance (R_s) over a large resistive range from 10 to 10^7 Ω/sq. [Fig. 2(a)]. The visible-light transmittance of ITO (200 Ω/sq.) with an anti-reflective coating and SWNT films with varying sheet resistances is shown in Fig. 2(b).

The SWNT film displays high transparency across the complete visible light spectrum. In comparison, ITO has a maximum transparency between 500 and 550 nm, at the expense of significantly lower transparency at other wavelengths. SWNT films demonstrate slightly lower transparency at 550 nm compared to the peak transmittance of ITO; however, SWNT films exhibit significantly higher transparency through the entire visible-light spectrum up to the infrared region. Wet processing, along with the ability to control sheet resistance while maintaining high transparency, makes SWNT a versatile coating material for flexible transparent electrodes.

Wet-Coating Application

Transparent conductive coatings can be deposited from aqueous SWNT dispersions that are applied as thin coatings (<100 nm) by conventional wet-coating methods. These include spray-coating, gravure, dip, spin, screen-print, and slot-die methods and attain a conductivity of 300 Ω/sq. after one deposition step. Recent experiments also include demonstration of SWNT deposition capabilities through roll-to-roll coating methods. SWNT coatings have been fabricated on 5- and 20-in.-wide PET webs (Fig. 3).



(a) (b)

Fig. 2: (a) Optoelectronic performance of SWNT grades. (b) %transmittance of various SWNT and ITO coatings.

Fig. 3: SWNT-coated 20-in.-wide PET web.

Additionally, SWNT coatings can readily be deposited onto small and large substrates utilizing spray-coating techniques that allow batch-type process requirements. As an example, SWNT coatings where applied as front and back electrodes (6 × 6 in.) in the light-emitting-diode (LED) illuminated logo displays shown in Fig. 4.

After the SWNT coating is applied, it can be infiltrated with a binder material, which further enhances the optoelectronic performance, increases adhesion and abrasion resistantance and improves mechanical and environmental durability. Today, SWNT coatings can be tailored readily to a visible light transmittance ranging from 80 to 99%, with a sheet resistance of 50–10,000 Ω/sq., respectively.

SWNT Durability

Carbon nanotubes are inherently flexible, strong, and chemically resistant. SWNTs can easily be bent without breaking and will spring back to their original shape with no degradation in properties. Quantitative evaluation of the mechanical durability of SWNT coatings has been performed in cyclic and tensile strain tests under ambient conditions. The sheet resistance was measured *in situ* during both tests, outperforming ITO films, which were demonstrated to be brittle and thus led to catastrophic failures. CNTs on the other hand, exhibited ductile responses leading to insignificant changes in resistivity.[1]

Fig. 4: Transparent SWNT electrodes in LED-illuminated displays.

Environmental stability of SWNT coatings is further enhanced by the appropriate choice of binder materials. SWNT networks are sensitive to environmental conditions found in the manufacture and use of the devices, which may lead to changes in sheet resistance. Fortunately, careful selection of the binder and processing conditions nearly eliminate the sensitivity of these coatings without sacrificing the optoelectronic properties of the SWNT coatings (Fig. 5).

Sheet-resistance stability under different heat-aging conditions has been thoroughly evaluated. Thermally stable SWNT coatings on PET at 100°C have been demonstrated (Fig. 5). It is further noted that SWNT coatings have been developed with excellent stability in applications that require elevated process and operation temperatures over 200°C. Thus, SWNT-based films, coatings, and electrodes can be protected not only against mechanical damage (*i.e.*, abrasions and scratches), but also against environmental stresses, including temperature, humidity, and ultraviolet light.

SWNT Patterning

In addition to the ability to tailor optoelectronic performance, ease of processing, and mechanical durability, SWNT coatings can be patterned by a variety of conventional methods. These include subtractive and additive methods. As an example, SWNT films have been patterned by depositing a negative image using a simple laser jet followed by removal of the initial material. Secondly, SWNT films can also be patterned by traditional photolithography techniques and laser ablation. And thirdly, ink-jet printing has also been demonstrated as a viable patterning technique.

Additional patterning methods include shadow masks, silk-screen, and gravure coating, all practical and relevant processes employed by the display community at large.

SWNT-Enabled OLEDs

Carbon nanotubes have attracted worldwide attention in recent years in applications ranging from biotechnology to electronics. Exploitation of SWNT's novel optoelectronic properties in transparent conductors is now well established.[2] Successful demonstrations of SWNT-enabled flat-panel displays such as organic-light-emitting-diode (OLED) displays are still relatively few, though early results show promise as an alternate anode material. The fabrication of high-performance OLEDs with SWNT anodes was recently reported. At a maximum brightness of 2800 cd/m^2, a luminance efficiency of 1.4 cd/A was achieved.[3] In another paper, OLEDs with CNT anodes on polyethylene terephthalate (PET) was also reported. This flexible SWNT-enabled OLED device yielded a 1.6-cd/A efficiency at a maximum light output of 3500 cd/m^2. Although performance of these display structures are not competitive with ITO, substantial improvements in the SWNT optoelectronic properties are expected as these materials are further developed and optimized to conform with OLED materials and manufacturing.

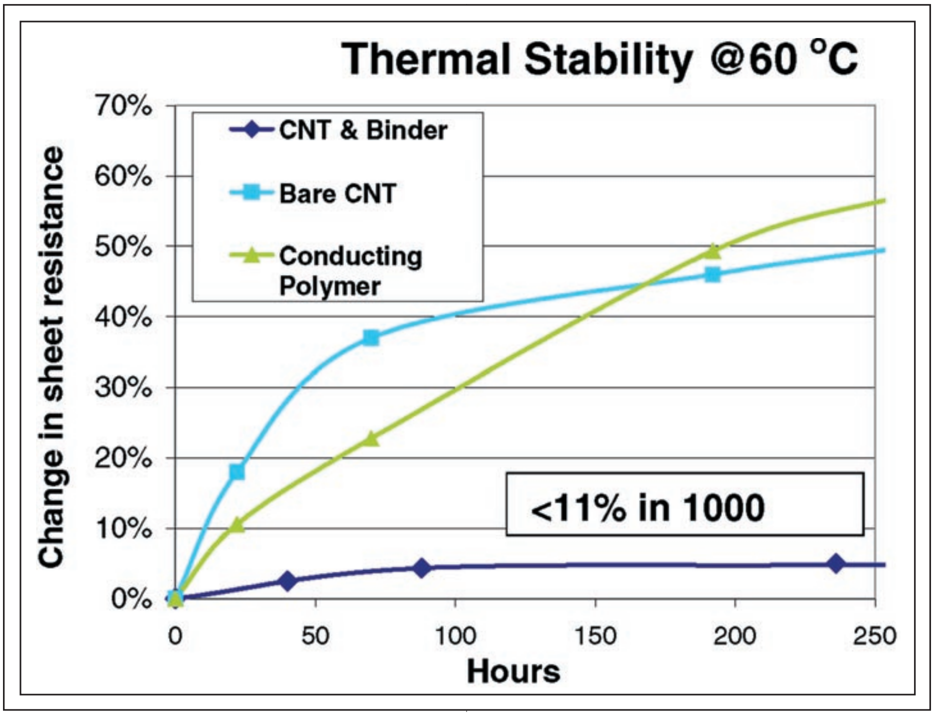


Fig. 5: *SWNT-coated 7-mil PET substrates. Control represents bare SWNT (300 Ω/sq.), whereas binders 1 to 3 represent various binder-chemistry options.*

Conclusion

The ideal transparent electrode for flexible displays is low cost and printable with tunable resistance, good transparency, flexibility, ease of patterning, and compatibility with roll-to-roll processing. SWNT coatings, especially on plastic films, can achieve a comparable optoelectronic performance to that of ITO and can be deposited with low-cost low-temperature wet-coating methods, eliminating the need for costly vacuum tooling and sputtering. SWNT withstands high temperatures and a variety of chemical environments including acids, making it compatible with other display materials and processing commonly employed by OLED fabricators. Thus, SWNT electrodes are a viable alternative to ITO for flexible-display applications, offering superior durability and flexibility, ease of processing (wet coating and patterning), low reflectance, and neutral color.

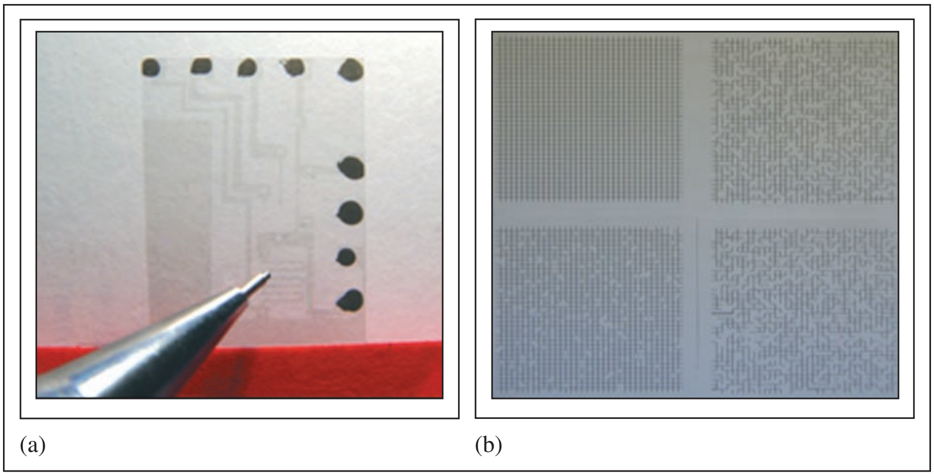


Fig. 6: *SWNT coating patterned by (a) ink-jet laser printing and (b) laser ablated to 0.100-mm fine-line fractal patterns.*

References

[1] M. Trottier *et al.*, *J. Soc. Info. Display* **13**/9, 759 (2005)].

[2] Z. Wu *et al.*, *Science* **305**, 1273 (2004).

[3] C. Aquirre *et al.*, *Appl. Phys. Lett.* **88**, 183104 (2006).

[4] J. Li, *Nano et al., Lett* **6**(11), 2472–2477 (2006). ■