Carbon-nanotube film on plastic as transparent electrode for resistive touch screens

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Abstract — Carbon-nanotube (CNT) films on plastic are incorporated as the touch electrode in a four-wire resistive touch panel. Single-point actuation tests show superior mechanical performance to ITO touch electrodes, with no loss of device functionality up to 3 million actuations. Sliding-stylus-pen tests reveal no loss of device linearity after 1 million stylus cycles. A CNT refractive index of ~1.55 leads to CNT touch panels with low reflection (<9% over the visible range) without costly anti-reflective coatings. CNT films on PET currently have 86% total transmission (including the PET) over the visible and 600 Ω/□, with lab scale tests giving 88% at 500 Ω/□. CNT films are neutrally colored (a*~0, b* ~ 1.5), low haze (<1%), uniform, and both chemically and environmentally stable. Unidym’s solution-based coatings can be printed directly onto both flexible and rigid polycarbonate using solution coating processes. Unidym films can be patterned using subtractive methods such as laser ablation with resolution down to 10 μm, or additive methods such as patterned gravure. CNTs are grown, purified, formulated into inks, and coated using scalable processes, allowing films to be attractive from a cost perspective as well.

Keywords — Carbon nanotubes, resistive touch screens, flexible, transparent electrodes.

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1 Introduction

Transparent electrodes are a necessary component in many modern devices such as touch screens, LCDs, OLEDs, and solar cells, devices which are growing in demand. Currently, these electrodes predominantly consist of vacuum-sputtered oxides, the most common of which is indium tin oxide (ITO). ITO, however, suffers from several problems, such as poor mechanical robustness, yield loss during manufacturing (often at the device level), high reflectivity, a yellowish tint, high cost, limited production capacity, and a dwindling supply of indium.1 Unidym solves these issues by replacing ITO with a thin film of carbon nanotubes (CNTs) printed on flexible polyester terephthalate (PET) substrates. 

2 Film manufacturing

2.1 Inks and coatings

There are three major steps in manufacturing Unidym’s CNT film product: CNT growth/purification, CNT ink formulation, and thin-film coating. Unidym has chosen scalable processes for each of these steps, enabling for the first time a commercial supply of CNT-coated film with excellent performance. Tubes are grown using thermal CVD with a proprietary catalyst/reactor. Purified CNTs are processed using proprietary catalyst/reactor. Purified CNTs are formulated into aqueous-based inks using a system that can produce enough ink per day to coat ~50,000 ft.² of product. Inks are formulated to the proper rheological profile for high-throughput coating using standard printing techniques such as spray coating, slot coating, ink-jet printing, and gravure [Fig. 1(a)]. Unidym has demonstrated production scale coatings of CNT films on plastic substrates up to 5 ft. wide at speeds up to 300 ft./minute [Fig. 1(b)]. For comparison, vacuum-deposited oxides such as ITO typically coat at 1–10 ft./minute, and use costlier vacuum deposition. The thickness of the CNT films can easily be varied by controlling both the concentration and wet laydown thickness of the CNT ink. Variations in CNT film thickness will affect the final film Rq and transmission.² By using a standard slot coater, final film resistance can be quickly and simply tuned from 100 up to 10,000 OPS (78–93% total film transmittance, including plastic substrate) using the same CNT ink by modulating the flow rate of the ink through the coating die. This is in contrast to sputtered oxide films, which are more difficult to continuously tune to the desired resistance.

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and cannot be easily made to have resistance greater than 1000 OPS since very thin ITO films tend to be extremely brittle. Unidym’s first product is 600 OPS and 86% total transmission in the visible region (film thickness ~10–20 nm). The final CNT film product also incorporates a polymer topcoat, whose primary function is to improve the adhesion of the CNT film to the plastic substrate. Unidym has demonstrated coating on PET substrates with clear, anti-glare, and/or anti-Newton ring hardcoats; the data in this publication is for PET with a clear hardcoat. Note that Unidym’s CNT ink can be coated on a variety of surfaces, including PET, polyethylene naphthalate, polycarbonate (PC), and glass, as well as on rough or curved surfaces, such as those found on anti-Newton ring hardcoats, without significant loss of performance. This may open up new applications, especially for flexible and curved displays where ITO has mechanical robustness issues.

2.2 Polycarbonate

Unidym’s wet-coating process enables coating of substrates inaccessible to ITO, such as rigid or flexible PC. This is important as companies seek to move away from fragile glass components, and towards durable and lighter PC substrates that give additional robustness to the product without sacrificing performance. ITO coating on PC has proven elusive, as the thermal coefficient of PC causes elongation and contraction that leads to cracking of the ITO layer. Typically ITO on PC has an order-of-magnitude higher resistance at a given transmission than ITO on PET.\(^5\) Currently, companies who seek to use PC are forced to laminate ITO on PET to a rigid PC backer using an optically clear adhesive. Direct coatings on PC are preferred, as it removes a PET layer, costly optically clear adhesive, and a manufacturing step. Unidym has demonstrated direct coatings of CNT on PC using standard wet-coating processes. As shown in Fig. 2, CNT on PC offers a much simpler device stack than the ITO/PET/PC laminate structure. It is also possible to coat both sides of a PC substrate with CNTs, which could have future applications in capacitive touch screens. Though the data in this publication focuses on CNT films on PET, the electrical, optical, and mechanical performance of the films on PC are largely similar.

2.3 Patterning

For both resistive and capacitive touch screens, the transparent conductor material needs to be patterned for proper device functionality. In four-wire and five-wire resistive touch screens, edge-deletion patterning is required, while in capacitive, more complicated patterns throughout the film are necessary. ITO films are typically patterned by screen printing of a wet acid etchant. However, this method generates hazardous chemical waste in the process, which is expensive to treat and not environmentally friendly. Also, acid etching of ITO films actually decreases its mechanical integrity, making it more prone to cracking near the etch points. Unidym’s CNT films, due to their high chemical stability, cannot be etched by the same acid-based methods. However, Unidym has demonstrated other methods for both subtractive and additive patterning, including oxygen plasma etching, laser ablation, and ink-jet printing. Laser ablation has many advantages over acid etch including no wet chemicals, no lithography, low operating cost, effectiveness, and ability to cheaply change the pattern. ITO can also be patterned by laser ablation; however, a higher fluence is needed which can damage the underlying substrate, introducing unwanted haze or other defects. Figure 3 shows CNT films that have been patterned by laser ablation. Laser-ablated patterns on CNT films have been demonstrated down to 10 µm with both electrical isolation (>10-MΩ resistance between conducting regions) and no visible
substrate damage. Laser patterning is cost effective and performed at high throughputs (up to 1-m/sec roll-to-roll) and has been demonstrated using both UV and IR lasers on PET and on PC. The resolution provided by laser patterning is sufficient for both resistive and capacitive touch screens. For resistive touch screens, where edge deletion is the only patterning required, an additive patterning step is feasible with wet-deposition techniques such as gravure. Additive patterning is largely preferred as it eliminates the need for expensive additional patterning steps.

3 Film properties

Unidym’s CNT films on PET have been extensively characterized with regards to their electrical, optical, and mechanical performance. Two primary properties of the film are the $R_s$ and the visible transmittance. When integrated into a four-wire resistive touch panel, current controllers can accept a certain range of input impedances. Typically, ITO with an $R_s$ between 250 and 500 OPS is used, though much of this is due to the ITO legacy, as there is no fundamental reason why films with $R_s$ greater than 500 OPS cannot be used (though when the $R_s$ gets too high it might introduce unwanted time constant delays). With the advent of new touch-screen controllers and minimal touch-screen redesign (for example, switching the $x$ and $y$ electrodes), CNT films with $R_s$ up to 800–1000 OPS could be used as the touch electrode with no degradation in touch-screen response. The transmittance is also important so that the integrated display will appear undistorted by the touch panel and is typically between 85 and 90% (the higher the better).

Figure 4 shows the four-point $R_s$ of Unidym’s CNT film vs. total transmission through the CNT layer and PET (measured using a Jasco V670 spectrophotometer with integrating sphere, weighted over the visible wavelength range). For a given CNT material and processing method, there is an inevitable tradeoff between $R_s$ and transmittance. Light adsorption (not reflection) limits transmission through CNT films; therefore, thicker films are darker, but have lower $R_s$. The red line shows current production-scale film performance on both PET and PC substrates of 86% transmission ($L* = 94.2$) and 600 OPS, which is already suitable for integration into many touch-screen products. Recent lab scale coatings on a PET substrate with a low-reflection coating opposite the CNT coating side, and using a higher purity, lower yield CNT, have shown results of 500 OPS and 85% or 300 OPS at 86%. The latter performance does not represent in any way the limit of what CNTs can achieve. Moderate improvements in tube purity, length, diameter, metal/semiconducting ratio, doping, formulation, and coating could conservatively lead to a film product with 500 OPS at 91% transmission ($L* = 96$) or 250 OPS at 88% transmission. As these fundamental optoelectronic parameters continue to improve, it will open up new opportunities for our films in various touch-screen applications beyond resistive and possibly for other markets in LCD, OLEDs, or solar.

Additional parameters beyond $R_s$ and optical transmission of these films need to be considered, including film stability under accelerated aging and touch actuation, uniformity, color, reflection, and mechanical properties. These are addressed below.

3.1 Reduced reflection

Unidym’s CNT films offer substantially lower reflection than a comparable ITO film without the need for any anti-reflective coating (which tends to distort the film color), due to its superior index of refraction match to most plastics such as PET ($n$ for CNT ~ 1.5–1.6; PET ~ 1.5; ITO ~ 2). Figure 5(a) demonstrates the low reflection of a CNT film on PET, with most of the reflection due to the PET film itself, in contrast to the higher reflection from most ITO films on PET (without the addition of costly anti-reflective coatings). The carbon-nanotube coating contributes less
than 1% additional reflection to that of uncoated PET. The low reflection from a CNT film improves the daylight readability by reducing unwanted specular reflection, or glare. Figure 5(b) demonstrates this principal, showing a photograph of an LCD monitor viewed outdoors in bright conditions through both a CNT/PET (top) and ITO/PET (bottom) film. Reflection from the ITO/PET film effectively reduces the contrast, making the display more difficult to read. Using PET with a low-reflection hardcoat leads to films with a total reflection less than 5% across the visible spectrum.

3.2 Color neutrality
An additional benefit of CNT films is that the CNTs absorb relatively equally across the visible spectrum. The benefit of this is that CNT films have a "neutral" color and will not significantly affect the colors from the display behind it. Figure 6 shows the $a^*$ and $b^*$ color coordinates for a CNT film, as well as various commercial ITO and conducting polymer films. The CNT film comes closest to (0,0), while the ITO films have a yellow tinge. A neutral color is beneficial in display applications so that the touch panel will not distort the image color. Recent coatings on a low $b^*$ PET ($b^* = -0.2$) can lead to CNT films with a $b^* < 0.5$.

3.3 Haze
Haze is the term for light that is scattered from the film surface as it is transmitted. Large haze values are typically not desired for touch-screen applications where optical clarity is important. Some transparent conductor technologies, such as silver nanowires, suffer from unwanted haze resulting from light scattered from the relatively large diameter (50–100 nm) wires. For CNT films, however, haze is not an issue, since the surface roughness of the films is on the order of 5–10 nm. Typically, the addition of CNT films contributes approximately 0.1–0.3% haze; therefore, the haze level is controlled by the choice of an appropriate substrate.

3.4 Uniformity
The electrical and optical uniformity of CNT films are important parameters for proper functionality of a touch-screen device. A uniform $R_s$ is especially critical for four-wire resistive touch screens, as it impacts the linearity of the touch response. The electrical uniformity of our CNT films is controlled by the film-thickness uniformity, which is set by the properties of the CNT ink and coating instrument. Typically, our films show a film $R_s$ standard deviation of 5–10% over an A4 sheet (measured in a 2-D array with 1-in. spacing), which is within the range desired by touch-screen manufacturers. This will be further addressed in Sec. 4. The optical uniformity is typically a 0.2% standard deviation over an A4 sheet.

3.5 Environmental/chemical stability
It is critical that a touch-screen device retain normal functionality after 2–3 years of use in typical daily conditions. These conditions may include high relative humidity (RH) and high/low temperatures. We performed accelerated aging tests on our CNT films at 60°C/90% RH. After 1000 hours at this condition, we find less than a 15% change in $R_s$ and less than a 0.1% change in transmission (film is allowed to equalize for 24 hours in ambient before measurement). The CNT film also must be able to withstand touch-screen manufacturing process steps, which sometimes includes a 150°C bake for 1 hour. Unidym’s product shows less than a 10% change in $R_s$ and less than a 0.5% change in haze after this aggressive processing step. Last, due to the relative chemical inertness of carbon nanotubes, Unidym’s films show less than a 10% change in resistance after a 10-minute soak in toluene, acetone, or isopropanol. CNT’s chemical inertness makes them insensitive to trace acids that may be found in various processing steps.

3.6 Mechanical properties
Unidym’s CNT films consist of a network of flexible nanotubes [see insert of Fig. 1(a)] on a plastic substrate. The mechanical properties of such a network of micron-long high-aspect-ratio wires is in stark contrast to a ceramic material such as ITO, which tends to be brittle and can crack under relatively low strains (~2%) leading to catastrophic device failure, while the CNTs can maintain film integrity (and more importantly $R_s$) up to strains of 20%. Unidym has previously shown that CNT films on plastic can be bent around a mandrel of 2-mm diameter with <20% change in $R_s$, while an ITO films shows a 1200% increase in resistance at the same
bending diameter. ITO films can be made more durable by laminating the ITO/PET film to a second piece of PET using an OCA, which can help reduce film stress. However, this adds substantial additional cost to the product, which CNT coated PET can avoid. The mechanical durability of nanotube films opens up new opportunities for touch panels, such as devices that are on a curved surface. Such a curved surface could introduce excess stress that would lead to quick failure in an ITO device, while the CNTs could withstand such stress. In fact, CNT devices could thrive in any market where rugged touch screens are needed.

4 Touch-screen integration

Unidym’s CNT films were integrated into a fully functional 10.4-in. four-wire resistive touch screen with the architecture shown in the bottom portion of Fig. 7(a). A CNT coated PET film with a clear hardcoat was used as the top electrode and an ITO-coated glass with spacer dots as the bottom electrode. The full stack was assembled into a touch panel in a standard fabrication line. This demonstrates the compatibility of CNT-coated films with current manufacturing processes and techniques, including application and curing of silver bus bars. The final device is shown in Fig. 7(b), and a slightly smaller touch panel integrated with a full-color LCD is shown in Fig. 7(c).

The mechanical robustness of the touch panel shown in Fig. 7(b) was measured using a single-point actuation tap test using a stylus with a radius of 0.8 mm and 250 g of force. A similar test was also performed on a commercial ITO touch panel. The curvature induced by the stylus creates high tensile and compressive stress which, in the case of ITO, leads to cracking of the conductive film and an asymptotic rise in the switch resistance. The end result is a panel that is inaccurate, unresponsive, and has poor resolution. The flexible, web-like topology of a CNT film provides natural stress relief, making it almost impossible to crack or break by such mechanical tapping. Figure 8 shows that a panel with a CNT touch electrode continues to operate with negligible change in switch resistance, long after an ITO panel has failed. Unidym has subsequently tested a device out to 3 million touch actuations without touch-panel failure. It should be noted that the actuation test was performed with the device under constant electrical bias of 5 V.

The mechanical robustness demonstrated by CNT touch panels promises to increase the lifetime and durability of current touch screens, while opening future applications in flexible and curved touch screens, where the ITO would crack quickly under the increased strains. A particularly weak point for ITO-based devices is near the edge bezel, where strain is maximized. CNT films show no such susceptibility to tapping at the edge bezel region. Thus, use of CNT films would decrease the needed bezel size, thereby increasing viewable area. Another overlooked, but important, benefit of CNT film robustness is the improvement in yield loss that occurs during film handling and device manufacturing in ITO-based devices. For mechanically demanding processing steps, such as ITO film lamination to a backer substrate, yield losses can exceed 30%; this would be a non-existent problem for CNT films.

An important touch-panel device parameter is response linearity, which should not change over time as the device is
used. To test this, we subjected the device to repeated cycles of a sliding stylus (Palm 3181WW) under a 250-g load. The stylus reciprocated against the device at 4 Hz, and the device was held under a constant 5-V bias. The device linearity was periodically measured every 10 000 strokes (up to 1 million strokes) by measuring the device voltage at approximately 4-mm intervals. Figure 9 shows that the device is linear over the area tested, and that the linearity does not change as a function of stroke number. This shows that the film $R_s$ remains constant over the 1 million sliding stylus cycles, indicating no damage to the film from the sliding stylus and no film delamination. Essentially, the device response does not change up to 1 million cycles using a sliding stylus, another indication of the robustness of Unidym's films.

Section 3.1 discusses the reduced reflection from CNT films compared with ITO. This translates directly to reduced reflection in touch panels incorporating the corresponding films. Figure 10 shows the reflection from a CNT/ITO touch panel, as well as from an ITO/ITO panel. The reduced reflection from the fully integrated CNT/ITO panel agrees qualitatively with the reduced reflection from the CNT film shown in Fig. 5. It is anticipated that using a CNT/CNT panel could further reduce the reflection.

5 Conclusions

The explosive growth in the demand for touch panels in displays (driven in large part by the iPhone) has increased the urgency of finding alternatives to expensive and brittle ITO-based devices. Unidym has demonstrated a scalable set of materials and processes that meets the needs of analog-resistive touch panels and with further improvements will meet the demands of other touch-panel applications as well. The ability to form a transparent conductive layer on PC is particularly important, as this is difficult to achieve with ITO. The ability to function under curved and stressed conditions without failure will assuredly motivate CNT-based films to be an integral part of future flexible displays. The replacement of expensive vacuum-based sputtering with aqueous-based roll-to-roll coating, coupled with the falling price of CNTs and rising price of indium, make CNT-based devices increasingly attractive from a cost perspective as well.9

References