Printed Touch Sensors Using Carbon NanoBud® Material

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Abstract

Carbon NanoBud® transparent conductive films and touch sensors were manufactured by aerosol synthesis, Direct Dry Printing® and laser ablation. Touch sensors with high contrast for outdoor readability, flexibility allowing folding, and sharp-angle 3D-formability are described. CNB™ film production has now started for high-quality touch applications.

Author Keywords

touch sensor; projected capacitive touch; transparent conductive film; nanomaterial; carbon nanotube; NanoBud; ITO replacement; printed electronics; flexible electronics; roll-to-roll manufacturing; display contrast; reflection; anti-reflective coating; direct bonding; Direct Dry Printing (DDP); In Mold Decoration (IMD); Film Insert Molding (FIM), In Mold Labelling (IML)

1. Objective

The user experience of current consumer electronics, and in particular touch displays, is limited, in large part, by the properties of existing transparent conductor materials used as transparent electrodes both in flat panel displays and capacitive touch sensors. We present progress in achieving "Beyond ITO" characteristics based on Carbon NanoBud® (CNB™) technologies that allow improved optical and mechanical performance, novel flexible and three dimensional form factors and reduced cost. This work makes a significant impact in enabling simultaneously 1) flexible or 3D shaped touch sensors, 2) high optical quality touch displays with almost no reflections and high contrast outdoors, and 3) cost effective manufacturing by dry roll-to-roll processing.

2. Background

Indium Tin Oxide (ITO) is the current industry standard transparent conductor material. ITO is a brittle ceramic which makes it unsuitable for flexible electronics. Further, due to ITO's high index of refraction, touch displays reflect external light and display images may become washed out in bright indoor and normal outdoor conditions. The effect can be reduced by using index matching layers in ITO sensors but this adds cost and complexity. Silver nanowires and different forms of metal meshes have emerged as ITO replacement materials. These offer benefits for large-area touch displays where the limited conductivity of ITO on plastic substrates is an issue. However, silver nanowires and metal meshes are metallic and hence reflect light and result in the display wash-out effect. Optical transmission losses in well-designed carbon nanomaterial based transparent conductor films are almost exclusively due to absorption instead of reflection. Hence, the display wash-out effect is reduced. Thus far, the usage of carbon nanotubes in touch sensors has been limited by the relatively large absorptive losses at relevant sheet resistivity levels, resulting in reduced display brightness.

To address the listed shortcomings of existing solutions, Canatu has developed a new carbon nanomaterial, the Carbon NanoBud; a hybrid of Carbon Nanotubes and fullerenes [1]. Hybridization is achieved directly in the material synthesis process and the resulting material combines the high funtionalizability of fullerenes with the high conductivity and robustness of nanotubes. Aerosol synthesis of carbon nanotubes has been demonstrated by Nasibulin et al. [2]. This method has been modified and scaled to produce commercial quantities of clean, lightly bundled, high crystallinity CNBs directly in the gas phase, thus eliminating the need for liquid processing.

Canatu has also developed a new thin film manufacturing method called Direct Dry Printing® (DDP) based on the work described in Kaskela et al. [3] and the thermophoretic technique described in Gonzales et al. [4] that allows direct synthesis and patterned deposition of CNBs by aerosol deposition. The combination of aerosol synthesis and DDP allows homogenous or patterned deposition on any substrate at room temperature and pressure, resulting in a simple, scalable, one-step, low cost and environmentally friendly thin film manufacturing process that improves the quality and performance of final products. Unlike traditional methods, no material degrading and hazardous acid treatments, sonication, surfactants or functionalizations for dispersion, purification and deposition are required. DDP is applicable to both sheet and roll-to-roll implementations and can be combined with traditional screen, gravure and flexo printing to allow the production of continuous rolls of complex, multi-layered components.

3. Results

3.1. CNB film and touch sensor manufacturing

Manufacturing process and line. We have built production capacity for medium volume manufacturing of CNB films and touch sensors (400 m^2 of CNB film/month or 20 000 mobile phone touch sensors/month) in Canatu's factory in Helsinki, Finland. Canatu's business model for high volume touch sensor manufacturing is to deliver CNB films for touch module manufacturers (Fig. 1). We are currently building a 600 mm wide roll-to-roll CNB deposition machine. The first unit will be ready for production in June 2014. The capacity for the machine is 8000 m^2/month and we are planning to have 4 lines installed by Q4 2014. The current facility allows capacity up to 500 000 m^2/month.

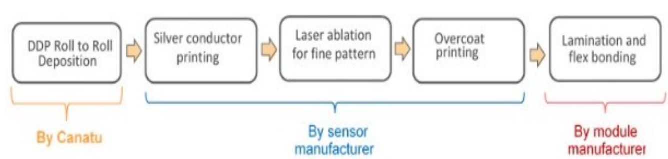

Figure 1. CNB touch sensor manufacturing process and business model for high volume touch sensor sales.

Carbon NanoBud synthesis and Direct Dry Printing on substrate. For this work, we have made homogenous and patterned depositions of CNB films on A4 and A3 sized sheets by combining the aerosol synthesis method with room temperature deposition based on a modification of the above described filter transfer technique. Consequently, high purity, low bundling and low concentration of catalyst material were achieved [5].

Fine patterning and conductive traces. Most projected capacitive touch sensors require fine patterning with minimum feature sizes of 25-50 µm. We have achieved this by laser ablation, which maintains the dry manufacturing process with no liquid handling and hence lower environmental footprint. Since no masks are required in laser ablation, the lead time for pattern changes is short. Only one process step is required, as opposed to 8 steps in photolithography. Our cost model shows that laser patterning is clearly more cost competitive than the more commonly used photolithography (see Fig. 2), and the low incremental CapEx cost for laser equipment as opposed to a photolithography line makes it more flexible for demand fluctuations and enables better line utilization. Canatu uses CNB patterning with 30 µm gaps in its production, enabling fully invisible patterns.

Cost per 500 mm x 500 mm sensor sheet	Photolitho	Laser ablation
Equipment (Depreciation)	$0.76	$0.71
Consumables/Utilities (OH)	$0.26	$0.01
Maintenance	$0.07	$0.06
Labor	$0.15	$0.04
Support Personnel (OH)	$0.24	$0.23
Scrap	$0.39	$0.15
Finance cost (10% interest rate)	$0.22	$0.21
Total direct patterning costs/sheet	$2.09	$1.43

Table 1. Cost of ownership of CNB laser ablation vs. ITO photolithography.

To complete the touch sensor, a conductive silver (Ag) layer was printed using a Microtec MTP-1100 TVC screen printing machine. Ag traces were fine patterned, either by laser ablation in the same process step as the CNB patterning, or for even better production efficiency, by direct screen printing. Canatu can now produce silver patterns down to 30µm/30µm lines and gaps with both laser ablation and screen printing.

It is important to note that metal mesh based touch sensors require very high tolerance and early design know-how of display pixel geometry to reduce the Moiré effect between the display and the sensor. Metal mesh manufacture is also demanding as the bonding equipment needs to be highly controlled. CNB sensors are display design agnostic due to the pattern invisibility and random orientation of the Carbon NanoBud deposition.

3.2. CNB film properties

Film transparency, reflectivity and haze.

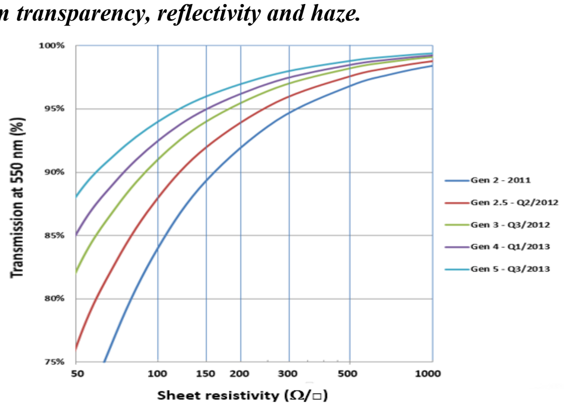

Figure 2: CNB film transmission vs. sheet resistivity for the current work (Gen 5) compared to Canatu's previous results from 2011-2013. Transmission is substrate-normalized.

Since 2007, Canatu has been able to double CNB film conductivity at a given transparency approximately every 12 months. Fig. 2 shows CNB film releases since 2011. We now manufacture Gen 5 films with the following properties: 100 Ω/□ at 94%, 150 Ω/□ at 96%, and 270 Ω/□ at 98%. In the lab, we can make 100 Ω/□ at >95%. High transparency is needed for enabling bright display images and pattern invisibility.

The haze of CNB film is negligible, as measured by the HunterLab Ultra-Scan VIS spectrometer (similar to ASTM D1003-95 standard) (See Fig. 3).

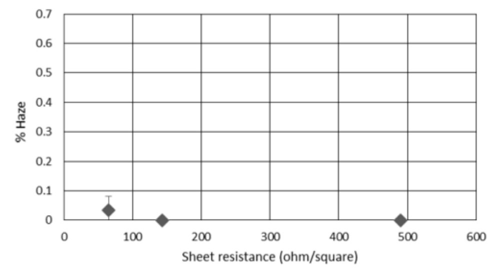

Figure 3. Haze of substrate-normalized CNB films as a function of sheet resistivity. Haze does not increase at low sheet resistivity it as does with AgNW and metal meshes.

Color neutrality. A transmission spectrum for a CNB film is shown in Fig. 4. The transmission spectrum was first measured with HunterLab from the film on a PET substrate (ASTM E1164 standard). Subsequently, the absorption of the PET was subtracted to obtain substrate normalized data. As can be seen, the optical absorption is uniform over the entire visible spectrum. The CIELAB color coordinates after normalization were measured as L*= 97.9 ± 0.1, a* = 0.0 ± 0.1, and b* = 0.6 ± 0.1 demonstrating that CNB films and sensors have no color distortion.

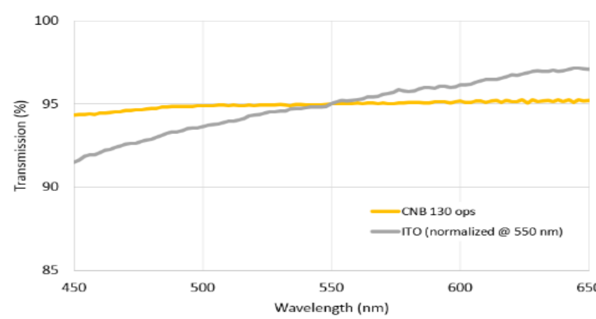

Figure 4. Transmission spectrum of substrate-normalized CNB films as compared to ITO.

Mechanical and environmental performance. CNB films were exposed to severe (180°) bending with results shown in Fig 5. Sheet resistance was shown to remain nearly constant over 30 000 bend cycles, after an initial change of a few per cent. In another similar test with 140 000 bend cycles, the change in resistivity was less than 7%. This demonstrates the applicability of CNBs for flexible and foldable touch products.

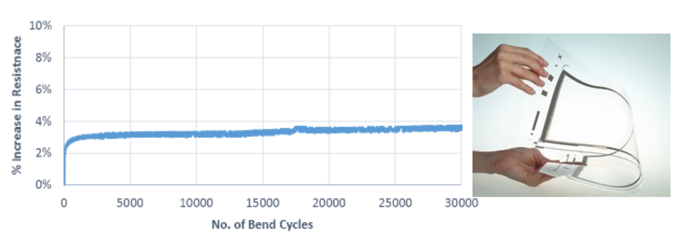

Figure 5. Change in resistivity for a CNB film on a 130 µm PET substrate, for repeated bends. The bending radius was 2 mm. Photo of a flexible CNB touch sensor.

We have applied Film Insert Molding (FIM) (aka In-Mold Decoration, IMD) as a standard industrial process for rigid 3D shaped touch devices. Fig. 6 shows a demonstrator with 120% stretching and 87° bending at 1-mm radius in an FIM device, demonstrating the high stretchability of CNB films. In collaboration with Bayer MaterialScience, we have made both 1-CNB layer and 2-CNB layer test devices for PF1 (Plastic-Film) and PFF (Plastic-Film-Film) type touch stack constructions. CNB layers, applied on polycarbonate Makrofol®DE film were 3-dimensionally shaped by a high pressure forming process [6]. The resulting inserts were injection backmolded with clear Makrolon® polycarbonate resin. In all test devices, CNB layers maintained their conductivity with a linear response to stretching.

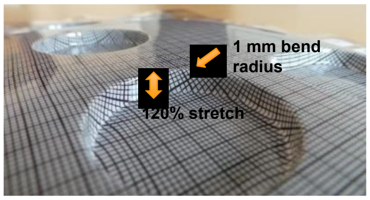

Figure 6. A Film Insert Molded demonstrator for CNB films with sharp angles and deep indentations.

We have exposed the CNB films to all typical consumer electronics environmental tests. All tests were passed (Table 2).

Test	Standard	Specification				
		ΔRs (Sheet resistivity change)	Δ%T (Transmission change)	ΔHaze	ΔE (Color change)	Adhesion (Cross cut and tape peel off, JIS K5600)
Room temperature storage	25°C/60% RH	Passed	Passed	Passed	Passed	Passed
Constant Temperature/ Humidity storage	IEC 68-2-78 (IEC 68-2-3) 60°C/90% RH	Passed	Passed	Passed	Passed	Passed
Thermal Cycle storage	IEC 68-2-2, IEC 60068-2-14 Test N, IEC 60068-2-14 Na, -40°C/ +85°C	Passed	Passed	Passed	Passed	Passed
High Temperature storage	IEC 68-2-2, IEC 60068-2-2 Dry heat tests, 85°C	Passed	Passed	Passed	Passed	Passed
Low Temperature storage	IEC 68-2-1 -40°C	Passed	Passed	Passed	Passed	Passed

Table 2. Environmental and accelerated aging test results of CNB films.

3.3. Touch sensors

We have made 13.3" diagonal CNB projected capacitive touch sensors with the manufacturing process as described. The touch stack was of Glass-Film-Film (GFF) type with sense and drive electrodes on separate PET sheets, laminated together and to the front glass with optically clear adhesive. The CNB film sheet resistivity was 220 Ω/□. The sensors were bonded with a flexible circuit board to the driving electronics, and the touch module assembly was "plug and play" retrofitted to an existing Intel Ultrabook reference design for comparison with the existing standard commercial ITO One-Glass Sensor (OGS) (Fig. 7). In this product, there is an air gap between the touch and the display. The assembly was made by SMK Corporation in Japan. An Atmel mXT224 chip was used as the touch controller. No modifications to the touch sensor chip were required.

Touch Module Type	Specular reflection	Diffuse reflection	Total reflection
CNB GFF laptop	8.6%	0.8%	9.4%
ITO OGS laptop	13.5%	0.6%	14.1%

Figure 7. A 13.3" CNB touch sensor integrated in an Intel Ultrabook reference design (left). Reflections from the touch display with CNB and ITO touch modules (right). There is an air gap between the display and the touch module.

The CNB touch sensor passed Windows WHCK tests and is, therefore, fully certified for Windows 8. As characterized by Atmel, the touch performance was found to be equivalent to commercial ITO sensors. The reflectivity, as measured by HunterLab (ASTM E1164) from the CNB GFF touch display, was significantly lower than that from the comparison ITO OGS touch display (Figure 7). In a bright office on a sunny day (2000 lux, 1000 cd/m2 specular light), the resulting 4.2:1 contrast is 30% better in the CNB based laptop than the ITO based laptop.

To compare CNB to ITO and metal meshes, we performed optical characterization of various touch modules at the Intel laboratory in Santa Clara. Table 3 shows that CNB touch modules have the lowest haze in this test.

Touch Module	Type	Sensor	Haze (%)
Carbon NanoBud	CNB	GFF	0.6
ITO OGS (no index matching)	ITO	OGS	3.3
Silver nanowires Metal Mesh	Mesh	GFF	1.4
Silver Metal Mesh #1	Mesh	GFF	2.0
Copper Metal Mesh #1	Mesh	GF2	1.6
Copper Metal Mesh #2	Mesh	GF2	2.0
Silver Metal Mesh #2	Mesh	GF2	1.3
IPAD 4 (Air)	ITO	GF2	1.0

Table 3. Optical characterization of Touch modules with a variety of transparent conductors.

To demonstrate touch on 3D surfaces, we have made a 12 cm diameter dome-shaped PFF touch sensor with a 15 cm radius of curvature (Fig. 8). The drive and sense sensor sheets were made using a 500 Ω/□ CNB film. An Atmel mXT768E controller was used and the sensor pattern was "Flooded X" type with 10-finger multi-touch, 254 dpi resolution and 12 ms report interval. There is a high transmission of >97% through the active CNB layers and the patterns are totally invisible.

In collaboration with TactoTek Oy, we also built a highly transparent 3D shaped demonstrator with slider, wheel, and button touch applying the FIM process with CNB on thin polycarbonate substrate and clear PMMA overmold (Fig. 8). The radius of curvature was 130 mm. TactoTek did the forming and injection molding with integrated LEDs.

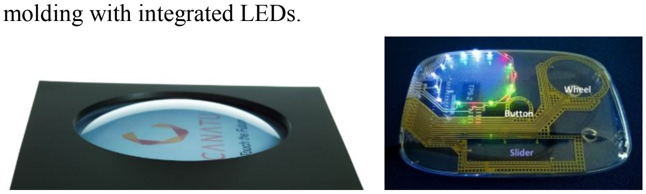

Figure 8. A 5" dome shaped CNB projected capacitive multi-touch sensor (left). A 3D shaped CNB FIM demonstrator with touch (right).

3.4. Optical demonstrators

To demonstrate touch display contrast in a direct bonded construction, we have built a 10" optical demonstrator to compare a TFT-LCD touch display having an ITO based 150 Ω/□ GFF stack to one with a 150 Ω/□ CNB GFF stack. The ITO film chosen for this demonstrator was industry state-of-the-art with complex index matching layers and optically optimized ITO. There was no air gap between the touch and the display. In order to demonstrate the lowest possible reflectivity, we added an AR coating to the front window (glass/air interface). As seen from Table 4, the CNB GFF device has 2.2% total reflectance. The total reflectance from the ITO GFF device is 3.4%.

Table 4 shows the breakdown of the reflection values in the touch display structure. The CNB sensor stack has no inherent reflections, hence, the 1.8% specular reflections in the GFF stack originate from the glass/AR/air interface and from the display (Fig. 9). For the ITO sensor stack, despite complex index matching layers, there are still 1% specular reflections from the ITO layers. By better optimizing the AR coating, using a less reflecting display, and optimizing the direct bonding materials, <1% specular reflections is feasible with CNB GFF sensors.

Direct Bonded Touch Module	Specular reflection	Diffuse reflection	Total reflection
CNB AR/GFF	1.85 %	0.36 %	2.21 %
ITO AR/GFF	2.91 %	0.47 %	3.38 %

Table 4. Reflections from CNB and ITO GFF optical demonstrators with AR coating.

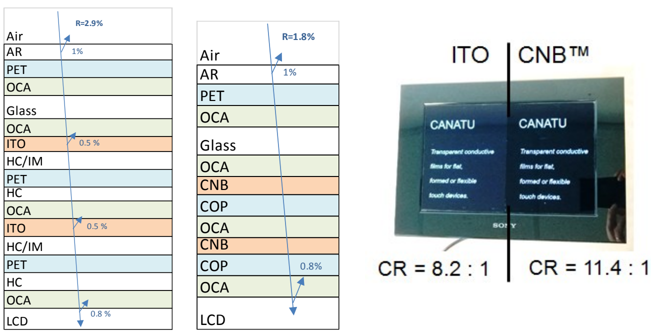

Figure 9. Stack diagram of direct bonded 150 Ω/□ ITO GFF (left) vs. CNB GFF (right). Photo of the demonstrator.

Contrast ratios of the combined TFT-LCD display used in this demonstrator (with ON Brightness of 220 cd/m^2 and OFF brightness of 0.3 cd/m^2) and the GFF touch stack were calculated using the measured reflections from the stacks presented in Fig. 9. The contrast ratio was calculated using the following formula:

$$CR_h = \frac{(I_0 + R_d * A_{mb} + R_s * Spec)}{(I_{dk} + R_d * A_{mb} + R_s * Spec)}$$

Rh	-the contrast at high ambient
I0	-white luminance of the display in dark room
Idk	-black luminance of the display in dark room
Rd	-diffuse reflectivity
Rs	-specular reflectivity
Amb	-diffused (daylight) ambient illumination
Spec	-specular (glare) light source

Fig. 10 shows the contrast ratio plotted as a function of ambient illumination for the direct bonded GFF devices with AR coating. In this simulation we have considered both diffuse ambient illumination and a bright specular source (i.e. a bright spot/area reflecting directly from the display). This combination is specified, for instance, in Vehicle Display standard J-1757. In a 2000 lux ambient/1000 cd/m^2 specular source, the contrast ratio of CNB based devices is 12:1 (40% higher the similar ITO device).

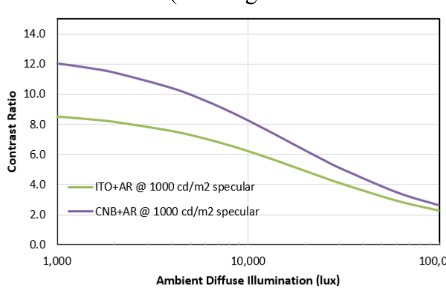

Figure 10: Contrast ratio for the direct bonded AR coated GFF devices with ITO and CNB.

We have also built an optical demonstrator with a 1-layer Glass structure (G1) where CNB film was deposited directly on a very low reflectivity window glass with AR coating, provided by Corning Inc. As seen from Fig. 11, a total specular reflectance of 1.2% was measured, with 0.5% from the window glass, 0.7% from the display, and 0% from the CNB film. The contrast ratio from this system is 22:1 in similar bright-light conditions as described above (2000 lux ambient/1000 cd/m^2 specular).

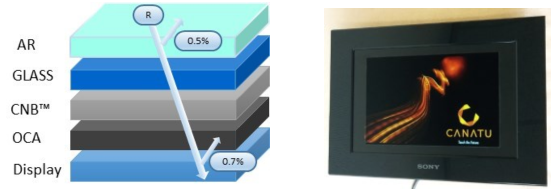

Figure 11: Ultra-low reflectance G1 touch system with 1.2% specular reflection.

4. Impact

We have ramped up the production of CNB films and built several products and demonstrators showing the applicability of the CNB material for high optical quality, flexible, and 3D formable touch sensors. A Windows 8 certified 13.3" Ultrabook touch module, a 5" multi-touch dome shaped demonstrator and a 3D shaped Film Insert Molded touch device were successfully produced. A CNB based GFF demonstrator is described with only 2.2% reflections and 40% better contrast in bright ambient compared to ITO. Further, a CNB based G1 touch concept with only 1.2% reflections and further 80% improvement in contrast is presented. It is shown that CNB films can repeatedly be folded 140 000 times at a 2 mm radius. For 3D shaped rigid touch, formability with 1 mm radius edges and 120% stretching was achieved.

CNB films are now a commercially viable option for high volume applications and for high quality flat, flexible and 3D formed touch sensors. Canatu is now in the prototyping phase with more than 30 customers worldwide for mobile phones, tablets, phablets, laptops, smart watches, digital cameras, automotive centre consoles, and white goods.

5. Acknowledgements

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