

## Integration of Carbon-Nanotube Common-Electrode in Active-Matrix Electrophoretic Plastic Display

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### Abstract

*We have successfully realized B/W 2.3-inch QVGA a-Si based Active-Matrix Electrophoretic Display using highly transparent, conductive and flexible carbon nanotube film instead of sputtered IZO. The CNT film was coated by roll-to-roll coating technique. In this way, we have shown the possibility of CNT in the reflective-based flexible display architecture.*

### Introduction

In past years, we have carried development of plastic display where liquid crystals or reflective electrophoretic microcapsules can be sandwiched between TFT and CF fabricated on plastic substrates instead of standard glass to make displays[1-2]. These displays are thin, robust and light-weighted and have huge application for E-book reader, mobile-handset to large-area sized information displays. ITO and IZO are popular materials for all display applications. They are typically deposited by vacuum-based sputtering processes at around 200°C and now possible at lower temperatures ~ 100°C on plastic substrates, though poor dimensional stability can lead to film stress due to cracking or film debonding from the substrate[3]. Normally 1000Å of IZO film on PEN gives ~ 85% of transmittance and ~50Ω/□ sheet resistance which is sufficient enough to drive displays on glass or plastic substrates. These excellent properties rose consumption and prices soared from \$60/kg to \$800/kg so alternative options such as conducting polymers [4], CNT [5],

metallic nanoparticles [6] based transparent films are seeing much development.

CNT based transparent conductive film (TCF) had been applied in various devices such as displays, touch-screens, solar-cells, TFT etc. [7-9] due to high opto-electrical and mechanical properties. They can be easily processed as thin-coatings using low-cost printing techniques such as spray or spin-coating, die/slit coating, inkjet printing on glass and plastic substrates such as PET, PEN, PES[10-11]. Presently, roughly for the same film thickness, CNT-TCF sheet resistance is typically an order of magnitude higher than ITO with slightly lower transmittance, but it is possible to improve their performance by improving material purity, high post-purification yield, and good dispersion stability and optimized coating processes.

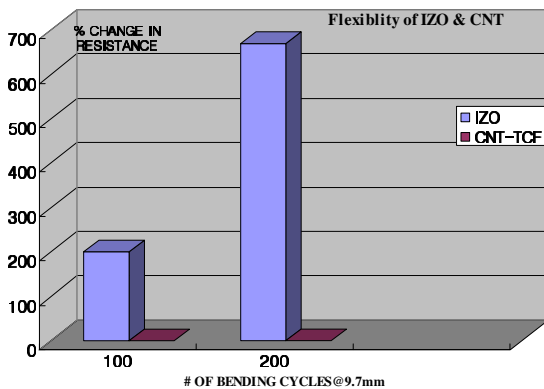
In this paper, we discuss employing high quality TCF of carbon nanotubes for the very first time as common electrode in an amorphous-silicon based active-matrix Black/White reflective Electrophoretic display (EPD) without color filter with all processes conducted on PEN substrate at temperature below ~ 150°C. The main objective of using CNT-TCF is to obtain high display quality on flexible substrate with minimum degradation under bending for long duration unlikely observed with IZO/ITO electrode. Therefore, this is an attempt to develop highly robust reflective based flexible display for mobile sized applications.

**Experimental Description**

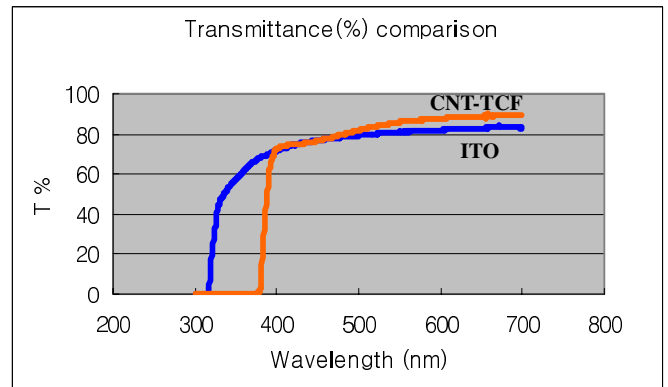
**I) TFT Backplane:** TFT backplane is fabricated at 130°C temperature using amorphous silicon on a 125 um thick heat-stabilized PEN substrate with inverted bottom-staggered TFT structure on 2.3inch PEN as described in [1-2].

**II) Preparation of CNT-TCF:**

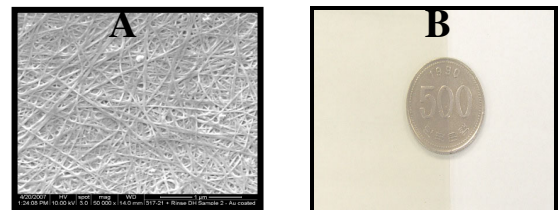
CNT-TCF (20-100nm) are coated on PEN substrates with non-vacuum process. This work was done in conjunction with US-based Unidym (CNT film-maker). The CNT inks are prepared by suspension techniques, followed by roll-to-roll coating on PEN substrate under room temperature and finally dried at room-temperature. For more details about the preparation of CNT films please refer [12]. CNT TCF has high transmittance ~85% (with substrate) and high conductivity ~1700S/cm. Also, these films are highly flexible with hardly any change in resistance at radius ~1cm bending for several hundred cycles compared to ITO & IZO as seen in **Fig. 1** and have high optical properties comparable to ITO films on PET as seen in **Fig. 2** and **Fig. 3** show CNT film's optical and SEM images. CNT-TCF was then coated with electrophoretic sheet ~30um thick at E-ink, USA. Finally, the stack of e-ink/CNT-TCF is laminated on 2.3" TFT backplanes by lamination as seen in **Fig. 4** and display module is done by OLB process.



**Fig. 1:** Graph shows comparison of %ΔRs versus bending cycles for CNT-TCF & IZO films.

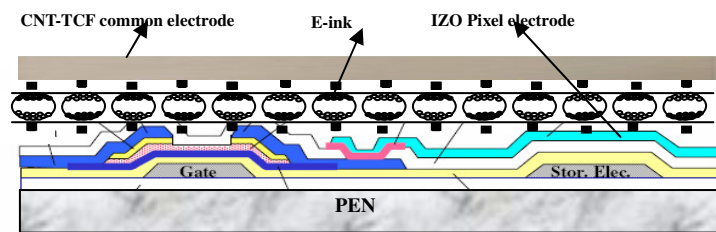


**Fig. 2:** Graph shows comparison of T% in visible spectrum for CNT-TCF & IZO films. This clearly indicates that CNT films are optically transmissive >80% and comparable to ITO.



**Fig. 3:** (A) SEM image of CNT network coated on PEN (B) Optically transparent CNT film on PEN.

This completed the process of integration of CNT-TCF as common electrode with TFT backplane to obtain 2.3inch AM-EPD with attached gate and data ICs for display driving.

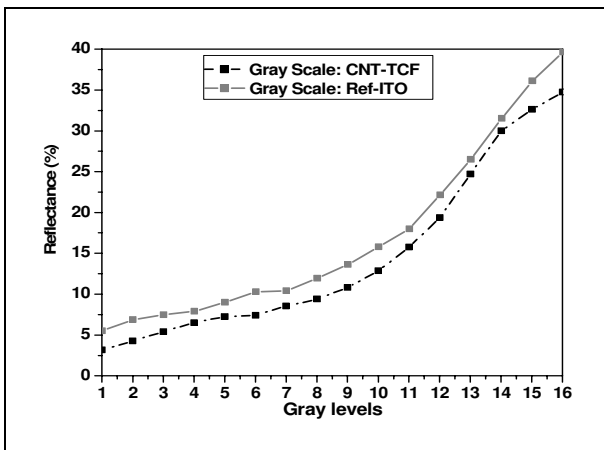


**Fig. 4:** Pictorial representation of the display structure of Pixel IZO (TFT) : eink : CNT common electrode

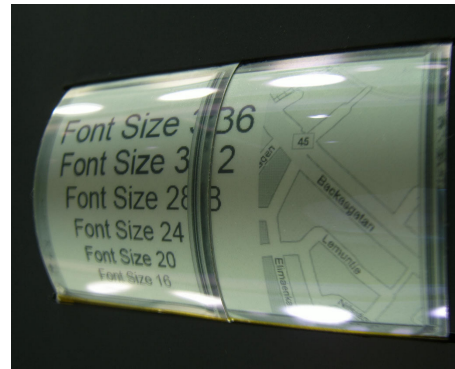
**Results and Discussion**

Once the CNT-TCF EPD panels were prepared using the above mentioned processes, they were then analyzed with programmed FPGA driving schemes to measure contrast ratio, gray-scale.

Gray-scale profile: We used ITO panel as reference sample whose maximum white reflectivity of the e-ink sheet is 40% though the black was high ~5.5% which resulted in contrast ratio of 7~8 typically reported for E-ink displays. However, in the case of CNT-TCF EPD panel, maximum white reflectivity was reported ~35% with black being below 3.5% hinting towards better readability for e-paper based applications with high contrast ratio ~10. The lower 'white' reflectivity of CNT panel can be accounted to high resistance of CNT TCF film than ITO which causes incomplete switching of the electrophoretic microcapsules under insufficient electric field between the CNT common electrode and the pixel electrode. The applied driving voltages were kept same for comparing the display performance. Lower 'black' reflectivity seen in CNT panel is related to the web-cob network of CNT tubes which improves the black reflectivity and enhanced the readability of the printed text. **Fig. 5** describes the gray scale profiles plotted for 16 gray levels in of the cases of CNT-TCF and Ref. ITO common electrode based EPD panel.

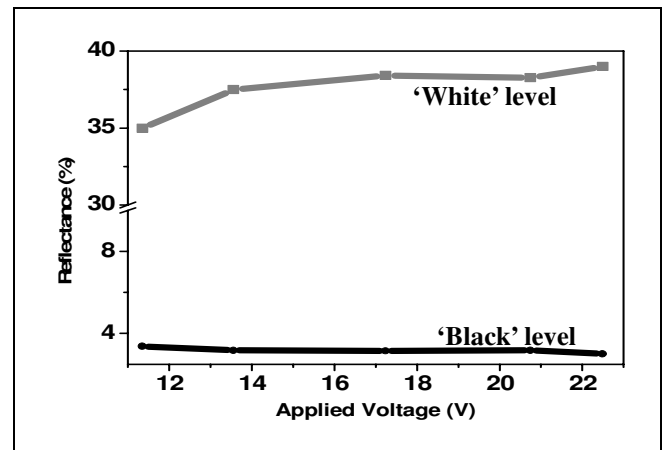


**Fig. 5:** Graph of Reflectance (%) vs. gray levels (16). It compares CNT-TCF-EPD panel (Black) with Ref. ITO based-EPD panel (Red).



**Fig. 6:** 2.3" Flexible CNT-EPD panel exhibited at SID 2008

**Fig. 6** shows high contrast image on CNT-TCF based EPD flexible display. To further enhance the reflectivity levels of 'white' and 'black' of the CNT panel, it was required to apply high voltages avoiding any sort of breakdown of the CNT film (high current carrying capability of CNT tubes ~10,000A/cm<sup>2</sup> in our case it was ~2mA), neither affecting the TFT performance nor the lifetime of the e-ink microcapsules. Due to higher resistance of CNT as compared to ITO, higher data voltages improved the contrast ratios. **Fig. 7** shows trend of the increasing 'white' reflectance and lowering 'black' reflectance when data voltages are increased from 10V to 20V without any damage to the panel components.



**Fig. 7:** 'White' level increases from 35% to 39% and 'black' level lowers from 3.5% to 3% when data voltage is increased from 11V to 22.5V.

Finally, High Temperature Operating Life (HTOL) or steady-state life test was performed on CNT-TCF based EPD display to determine the reliability of the device under operation at high temperature conditions of 60°C over an extended period of time of 160hours at room humidity in the oven chamber. This test was done to check the degradation of optical or electrical characteristics of CNT-TCF or the assembled structure of EPD under such conditions. There was no loss in the image quality or EPD switching time before and after this test.

### **Impact and Conclusion**

Due to several reasons such as soaring Indium prices and inherent film's brittleness, this is an intentional effort from our side to develop a flexible electrode based on carbon nanotubes which can be easily and cost-effectively coated on various substrates such as glass, plastic substrates and can be easily applied for the fabrication of active-matrix based reflective B/W 2.3inch electrophoretic plastic display. CNT-TCF used here holds superior optical-electrical properties which greatly enhanced the display outlook by providing better contrast ratio and higher readability that are essential requirements for e-paper based applications in the fast-spreading era of e-readers, slim and robust mobile phones while giving them a greater degree of flexibility. These results greatly indicate the usage of CNT based electrodes as a successful ITO replacement technology in display area.

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