Alternative Displays

Carbon Nanotube TFTs and Flexible Substrates

In the July issue of *Mobile Display Report*, we discussed a single-wall carbon nanotube (CNT) thin-film transistors (TFTs) are now possible for flexible displays and electronics, thanks to breakthroughs from the collaboration between the University of Stuttgart, Germany, and Applied Nanotech, Inc (ANI), a subsidiary of Applied Nanotech Holdings Inc. (OTC:APNT) (Austin, TX; www.appliednanotech.net). Now, we follow up with some additional details and insights.

The team announced June 26 it had obtained improved yield from its proprietary printing method, which avoids expensive photolithography. Furthermore, high mobility (100 cm2/Vs) and high on/off ratio (10^5) were achieved, which is far better than printed TFTs using organic semiconductors.

Such high mobility means these TFTs can be made small enough to avoid obscuring too much light, and therefore do not need to be transparent or hidden on the other side of substrates or display layers. The on/off ratio compares with a value of under 10 for previous attempts at the University of Maryland in 2005, in which printing of CNTs also was used.

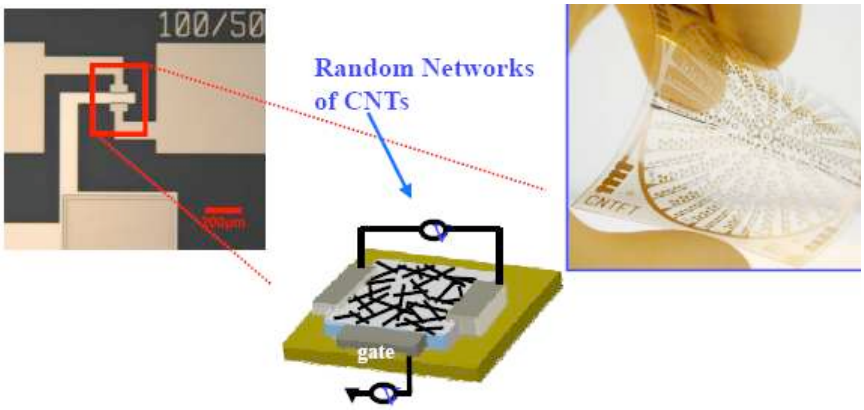

Illustration of random network CNT-TFTs (Courtesy of ANH)

No details were given of the precise yield, pending more data, or the particular printing method used, but ANI said ink-jet and microcontact printing methods may work. Dr. Zvi Yaniv, president and CEO of ANI, said yield is likely to be more a function of CNT purity, particularly semiconducting versus metallic types. Improvements in preparing purer CNTs has enabled monolayer CNTs to form the TFT semiconducting channels, which avoids the tremendous variations in mobility and threshold voltages found earlier. ANI considers the additional costs of higher purity to be inconsequential because so little of the material is needed in a display.

In the past, the significant proportion of metallic rather than semiconducting CNTs led to lower on/off ratios, and this can short-circuit the transistor. In fact, a previously reported method of removing the metallic type was by attacking with nitronium ions (NO2+) in a mixture of nitric and sulfuric acids (e.g. Cheol-Min Yang at Sungkyunkwan University, Republic of Korea, *J. Phys. Chem. B*, 2005, 109). ANI has its own methods, but also buys CNTs from other

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suppliers, and some of the latest separation methods are said to be more commercially viable and also allow selection of CNTs having the same "chirality."

Dr.Yaniv said, "Chirality relates to the skew of the rolled-up graphitic sheet of carbon atoms. This determines the semiconducting energy band gap affecting the mobility and threshold voltage." So, having CNTs with all the same chirality allows a smaller variation in the mobility and threshold voltage.

Of particular interest for flexible displays, electronic circuits and sensors is the ability to deposit at low temperature compatible with flexible plastic substrates. For more information about ANI's thin-film transistor approach see *Solution-deposited carbon nanotube layers for flexible display applications*, published in *Physica* E 37, Issue 1-2 (March 2007). There, researchers obtained a mobility of 1cm2/Vs, but not yet the homogeneity and reproducibility that has been addressed in this latest work.

Interestingly, Dr.Yaniv agreed that any adsorbent from the atmosphere on the CNTs can change the TFT characteristics, and that encapsulation by passivation will be necessary. But he said effects of gas and water vapor on the gate part of the TFT is less severe than for TFTs made with a-Si. (See also plastic vs. metal foil substrates as mentioned in the FlexTech Alliance contract searching for other metal foils besides stainless steel.) Overall, Dr. Yaniv did not see a problem with lifetime for these CNTs.

"The collaboration with the University of Stuttgart is very productive," he said. "Their expertise and facilities for microelectronic processes are well known and are very suitable for our need to transition from an idea to a proof of concept." The university's emphasis was on the deposition of CNTs in flexible displays, while ANI concentrated on the CNT material.

Dr. Yaniv maintains that there will be no problem going up in substrate size for larger displays or lower-cost volume production as the equivalent to large mother glass. Compared to organic TFTs, the numbers of addressed pixels should be greater, although any need for very short channel lengths may limit conductivity as the "percolation" mechanism for the fishnet monolayer of CNTs may not work. Ultimately, this might limit the pixel density, but the specific number has yet to be determined, and depends also on the final levels of the metallic CNT impurities. Furthermore, it appears the CNT-TFTs are compatible with the electrical requirements of all the applicable flexible display technologies, although the initial development work is with LCDs.

An attribute for use in displays is the transparency of electrodes. In related work on use of transparent CNTs as replacement for the usual thin-film transparent indium tin oxide (ITO) pixel electrodes, Prof. Dr. Ing Norbert Fruehauf at the University of Stuttgart presented a paper in May at SID '08 revealing a working demonstration of a 4-inch diagonal 320 x RGB x 240 a-Si TFT-LCD made in this way. Prepared entirely at the university's facilities, CNTs were deposited by a low-cost spray method. Sheet resistance for electrodes does not need to be so low, but high transmittance is more important. The researchers found purified CNTs prepared by the HiPCO process gave a transmittance up to about 94% for a sheet resistance of 2,000 to 3,000 Ohms/square. Using conventional a-Si TFTs with such electrodes resulted in an on/off ratio of 10^6 and mobility of 0.4 -0.6 cm2/Vs.

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APNT is a holding company with wholly owned operating subsidiaries Applied Nanotech and Electronic Billboard Technology Inc. (EBT). ANI's business model is to license its technology to partners that will manufacture and distribute products using the technology. Dr. Yaniv said, "Ideally for us would be to find a strategic partner that would want to take this to a pilot line." Together, the companies have more than 250 patents or patents pending, with at least one on this development, and one held by the University of Stuttgart. - *Paul Beatty*

Mobile Display Report is a technology and business newsletter covering the smaller sized display industry, published by Insight Media, Norwalk, CT, 203-831-8464. The remainder of this Mobile Display Report with further discussion of CNT developments is available through the publisher, Insight Media www.insightmedia.info

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