Carbon Nanotube Purified Ink-Based Printed Thin Film Transistors: Novel Approach in Controlling the Electrical Performance

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In this paper we present a comprehensive study of the solution-based printed carbon nanotube purified-ink devices while introducing a new idea of controlling the electronic performance of these devices. One of the most important concerns in nanoelectronics is whether the nanotube-based devices will ever enter the reality world of circuit designs? What are the fundamental and critical issues to be resolved? Which parameters affect the device performance most? A comprehensive study of the relationship between mobility, on/off ratio, and nanotube network density is presented for the first time in detail. This study reveals a clear road map towards experimental control over the performance of solution-based nanotube thin film transistors for a wide range of state-of-the-art applications.

The devices are fabricated on Si wafer (as a back-gate) with 300 nm oxide cap as the dielectric. The surface of the oxide is chemically treated with the self-assembled monolayer (SAM) of 3-aminopropyltriethoxysilane (APTES) as described in [1, 2]. Then about 20-40 μL of 99% semiconducting (determined by spectroscopic techniques) nanotube ink is put on top of the modified wafer and left for drying in ambient temperature. The source drain electrodes (Pd/Au) are deposited using e-beam evaporation. Different gate lengths from 10 to 100 μm are designed to study the effect of channel length while the channel width is fixed at 100 μm. The schematic of the process and fabricated thin film transistor is shown in figure 1 followed by the I-V characteristics of a sample device in figure 2.

Mobility and on/off ratio are the most important figures of merit, which have been explored in detail in this work. In addition, for the first time the network density and its critical impact on the device characteristics has been studied. Here we established a new idea to control the nanotube network density for modifying the performance of the devices. A fundamental relationship between mobility and on/off ratio was found, which has not been illustrated in any previous works (demonstrated in figure 5). More importantly, we discovered a tight correlation between the density of the network versus the mobility and on/off ratio that has also been overlooked in all printed nanoelectronic research studies so far. It has been presented here that the impact of network density is very crucial therefore, no comparison in any research work can be validated without taking this parameter into account. In fact, we offer that by controlling the network density we are able to adjust the device's characteristics in the most efficient way. The network density variation is obtained through managing both the surface treatment and the nanotube solution density prior to deposition. Mobility of more than 90 cm^2/V-s is obtained which is the highest reported so far. Comparing to state-of-the-art literature [2, 3], we are able to improve the mobility by at least a factor of 2X (more than 10X comparing to some other works) while reasonably maintaining the on/off ratio [2]. Besides, the on/off ratio of more than 100,000 shows 10X improvement comparing to similar works in the field [3]. Figure 3 to 5 demonstrate the relationships between mobility, on/off ratio, network density, and channel length. Figure 3 shows that by increasing the channel length, mobility will also increase. On the other hand, at a fixed channel length, mobility can be changed by altering the network density (as described in figure 4) which is the most critical key point for designers. Indeed, the effect of density on on/off ratio can be explained as well (more detail in [1]).

Thin film transistors (TFTs) were fabricated using solution-processed purified carbon nanotubes. Electrical measurements show mobility of more than 90 cm^2/V-s (2~10X improvement) and on/off ratio of more than 100,000 (10X improvement), compared to previous works. For the first time, the density dependence of the mobility and on/off ratio has been investigated showing a strong relationship between the density of the nanotube network and the devices' performance. Higher network density will increase the mobility while decreasing the on/off ratio. A comprehensive range of density from 10 tubes/μm^2 up to high end of 100 tubes/μm^2 was presented. This control method on the network density results in obtaining a wide range of mobilities and on/off ratios, which is critical for the broad market in printed electronics as well as CMOS and RF technologies. This work introduces a clear road map for a comprehensive range of nanotube-based transistor applications using semiconducting nanotube network. The presented parameters and techniques play a critical role in performance of carbon nanotube network transistors, which indeed is valuable for circuit designers. Based on these results, practitioners can now modify their circuits for a wide range of applications.

[1] N. Rouhi, *et al.*, "Fundamental Limits on the Mobility of Nanotube-Based Semiconducting Inks," *Advanced Materials,* vol. 23, pp. 94-99, Oct 26 2010.
[2] M. C. LeMieux, *et al.*, "Self-sorted, aligned nanotube networks for thin-film transistors," *Science,* vol. 321, pp. 101-104, Jul 4 2008.
[3] D.-m. Sun, *et al.*, "Flexible high-performance carbon nanotube integrated circuits," *Nature Nanotechnology,* February 2011.

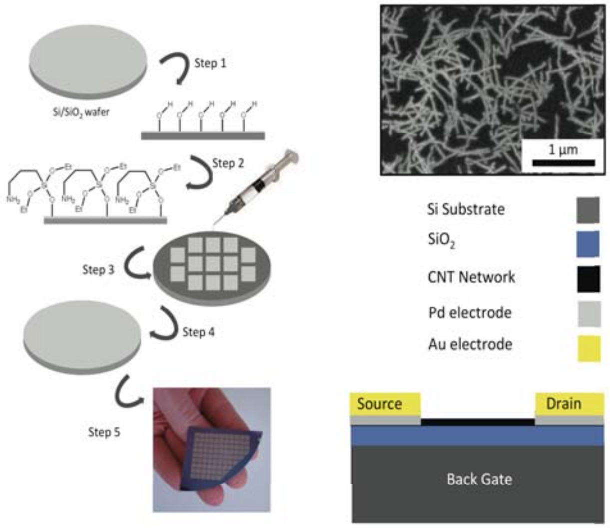

Fig. 1. Fabrication process and SEM image of nanotube network

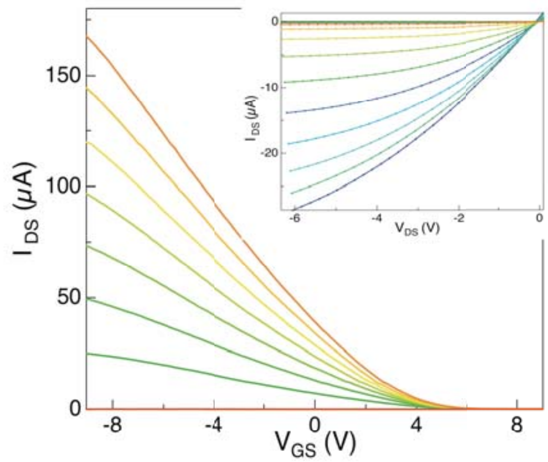

Fig. 2. Depletion curve (V_G : +10 ~ -10 V, with 2 V increment, V_{DS} : 0~7 V with 1 V increment). I_{DS}-V_{DS} in the inset

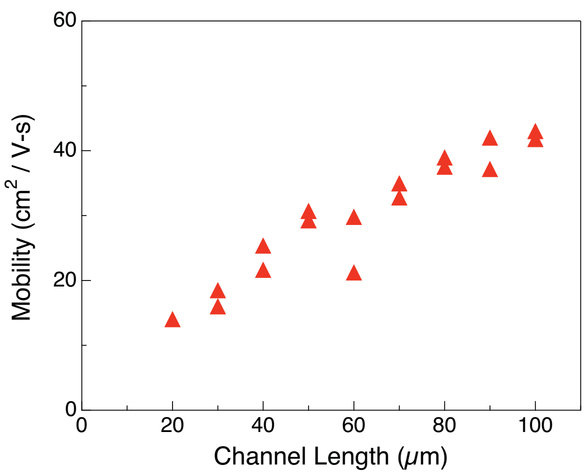

Fig. 3. Mobility vs. Channel length (moderate network density)

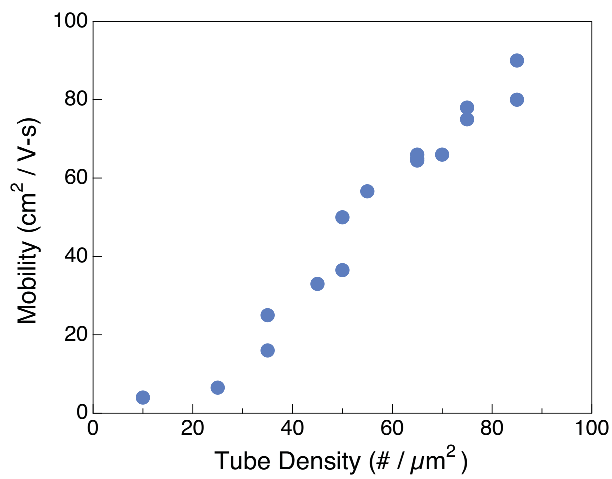

Fig. 4. Mobility vs. Network Density

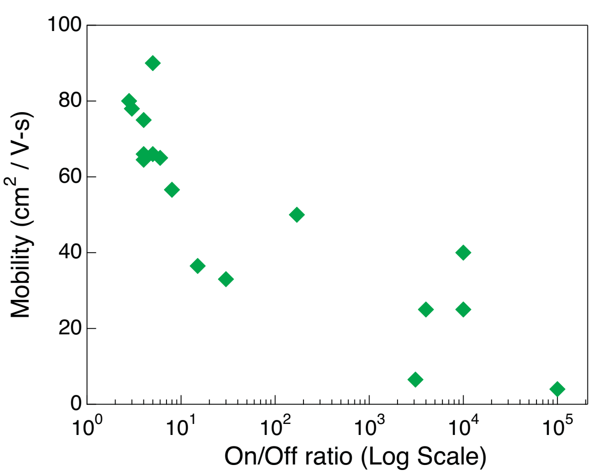

Fig. 5. Mobility vs. On/Off ratio

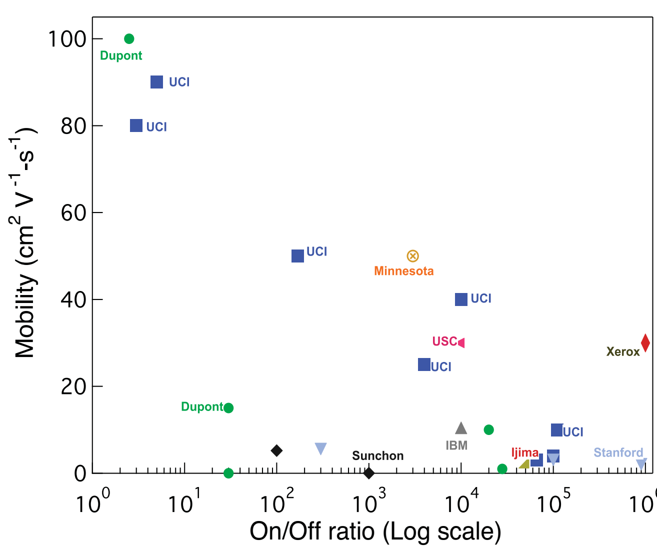

Fig. 6. Mobility vs. On/Off ratio (literature review)