

Top-gated Thin Film FETs Fabricated from Arrays of Self-aligned Semiconducting Carbon Nanotubes

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Carbon nanotube field effect transistors (CNTFETs) exhibit superb device characteristics. However, at present, the unsolved problem of non-preferential synthesis of metallic and semiconducting nanotubes, difficulty in placement, and low on-state current in single tube devices make difficult the direct integration of CNTs into electronic devices. While CNTs also exhibit interesting optical phenomena at the single tube level, the small CNT cross-section makes measurement a challenge. To increase the signal level requires a large effective cross-sectional area of aligned nanotubes in order to preserve the anisotropic optical effects. Here we present a new approach for making active CNT electrical devices and demonstrate the first aligned CNT array FET from 99% pure separated semi-conducting nanotubes. Through evaporation-driven deposition of predominantly semiconducting nanotubes from the liquid phase, we have fabricated aligned, thin-film CNT devices with high on-state currents. The fabrication scheme presented here provides a versatile production method translatable to other substrates such as flexible plastics.

We present thin-film electrical devices with dense, aligned carbon nanotubes as the active channel material. Surfactant encapsulated single-walled carbon nanotubes (SWNTs) synthesized by arc discharge are separated by electronic type using the technique of density-gradient ultracentrifugation [1]. The resulting solution is enriched with semiconducting SWNTs, as evident from the absence of the M_{11} transition in the UV-VIS absorption spectrum (Fig. 1) characteristic of metallic NTs. Packing of the SWNTs into dense aligned arrays is achieved through evaporation-driven ordering [2]. Following evaporation samples are rinsed with DI water and imaged by AFM (see Fig. 2a). Scanning micro-Raman measurements confirm the high degree of CNT alignment (Fig 2b), as the G-band signal is 1000 times stronger for incident light aligned parallel to the orientation axis compared with incident light perpendicular to the axis. Prior to device fabrication samples were annealed at 600°C to remove surfactants and other organic contaminants to ensure good contact quality. Electrical devices as shown in the Fig. 3 schematic are produced by defining source and drain contacts on top of SWNT arrays by Electron Beam Lithography (EBL) and metal evaporation. A second EBL step defines a protective oxide mask for the devices while removing extraneous CNTs by O_2 plasma. The mask is then removed and a third and final EBL step defines a region for top gate deposition (Fig. 4). The width of the devices are $W \sim 10\mu\text{m}$ and channel lengths vary from 500nm to $10\mu\text{m}$.

Transport characteristics are presented for a typical device of length $L=4\mu\text{m}$ and width $W \sim 10\mu\text{m}$ (Fig. 5). We observe an on/off ratio of more than 4 orders of magnitude and on-state conductance higher than $10\mu\text{S}$. This level of conduction is expected from arc discharge CNTs ($d \sim 1.1-1.6\text{nm}$) in percolation driven transport. Measurement of ~ 50 such devices allowed us to explore the relationship between on-state current, on/off ratio, and device length (Fig. 6). The shortest devices carry large currents but have a poor off-state behavior. As the device length increases, the on/off ratio grows rapidly without significant degradation of the on-state current. Balancing these trade-offs we find the optimum device length to be $L \sim 4\mu\text{m}$. Also notable is that the ensemble of tubes in each thin film FET reduces the device-to-device variation usually observed in CNT based transistors (Fig. 6). With their superior electrical properties we believe that these novel CNT array FETs open up new possibilities in thin film electronics.

[1] Arnold et. al., Nature Nanotechnology 1(2006), 60-65

[2] Huang et. al., Nanotechnology 15(2004), 1450-145

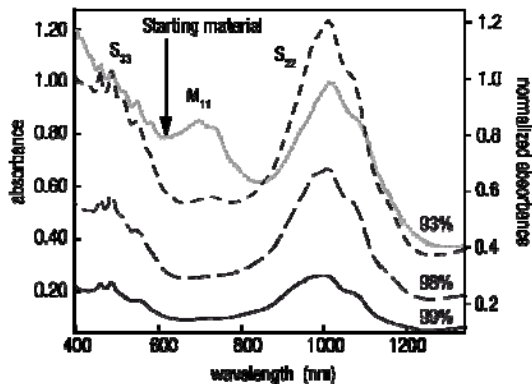


Figure 1 UV-VIS absorption spectra for unsorted NTs (light gray) and separated semi-conducting NT samples of purities ranging from 93% to 99%

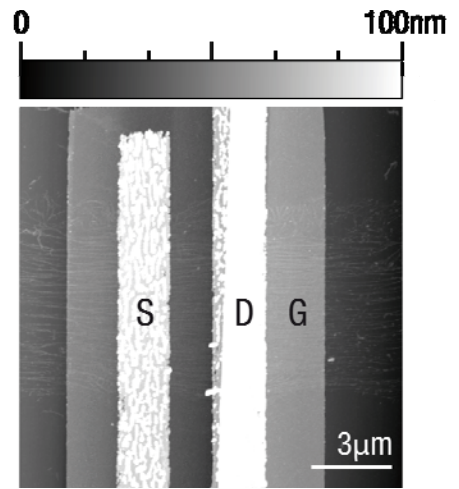


Figure 4 AFM image of a typical device. The electrodes (white) are overlapped by the top gate (gray).

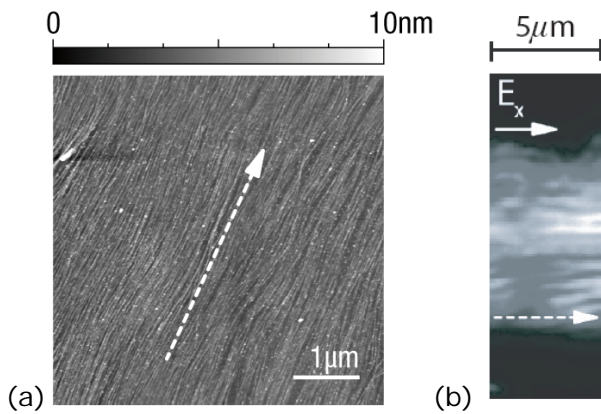


Figure 2 (a) AFM image of NT array (arrow indicates orientation axis); (b) Raman image showing G-band intensity of the aligned NT array (incident light polarization parallel to the orientation axis)

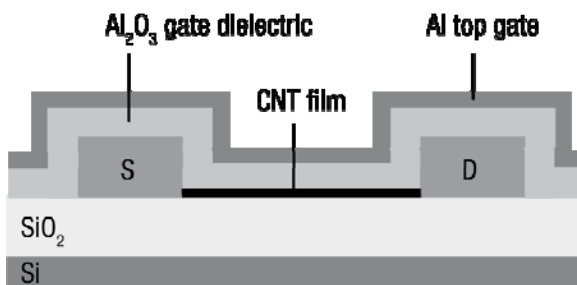


Figure 3 Schematic of aligned NT thin film device. Electrodes are Ti (1nm)/Pd (30nm)/Au (20nm). The top gate stack is composed of Al₂O₃ ALD (15nm) followed by Al (6nm)/Au (2nm) and allows 50% optical transmission.

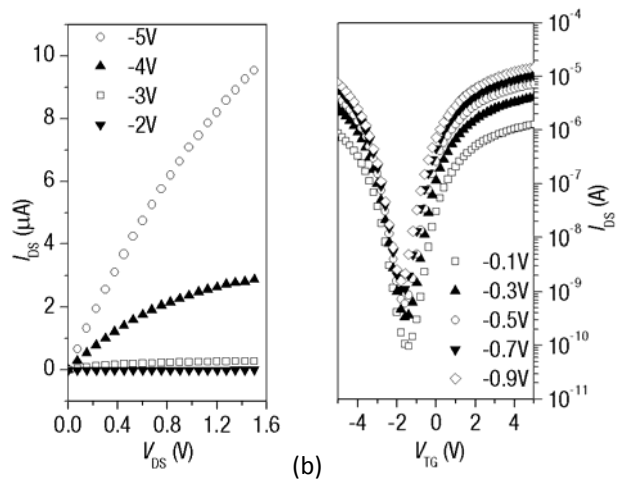


Figure 5 Electrical transport characteristics for typical $L=4\mu\text{m}$ device. (a) I vs. V_{DS} at different values of V_g ; (b) I vs. V_g taken at fixed values of V_{SD}

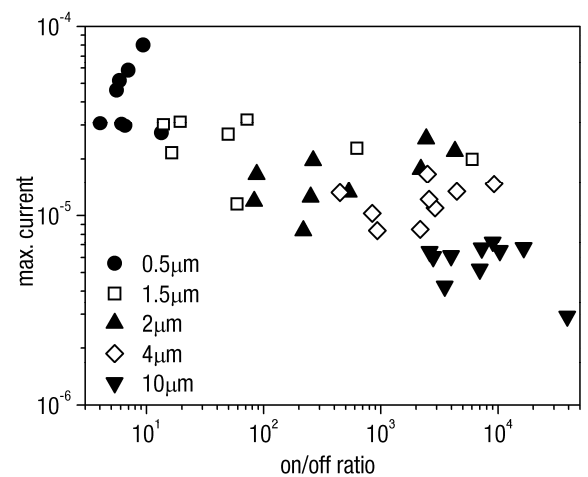


Figure 6 On-state current vs. on/off ratio for all measured devices