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Self-Assembled, Deterministic Carbon Nanotube Wiring Networks

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SUPPLEMENTAL MATERIAL

Crossbar Fabrication Parameters The crossbar preparation procedure is described in Figure Ap1. The first set of deposition electrodes were defined by optical lithography, deposited using electron beam evaporation, and consisted of 5 nm chromium followed by 30 nm gold. Electrode gaps were 10 micrometers, and the electrode length was 1.2 cm. The excessive length of these electrodes was designed so as to minimize the effects of fringing fields that can occur at the electrode boundaries. Such fields will modify the deposition process and lower the alignment quality.

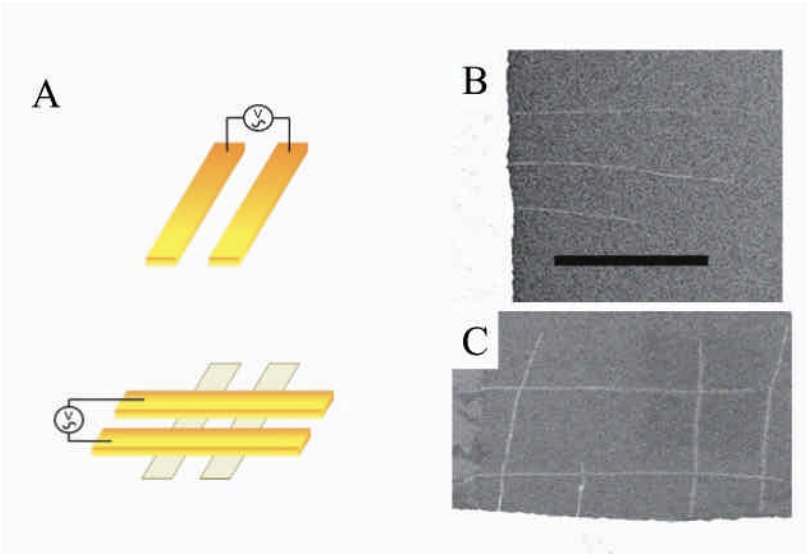

Figure Ap1. Schematic of the crossbar fabrication process. A. Orientation of top and bottom deposition electrodes. In the lower figure, the relative orientation of the first set of electrodes to the second set is shown, even those electrodes are actually removed after the first layer of SWNT ropes has been deposited. B. Scanning electron micrograph (SEM image) of three SWNT ropes that were deposited during the initial deposition process. C. SEM image of an assembled crossbar structure. Note in this picture that the first electrode set was not completely removed, and traces of it can be seen at left. These traces are organic residue (as send by energy dispersive x-ray analysis), and not metallic material. The second electrode set is the white, uneven border at the base of the image. The scale bar in B. is 1 micrometer, and is applicable for both SEM images.

Deposition conditions were 20 Volts (peak-to-peak) AC voltage amplitude at 4 MegaHz for 5 – 15 minutes. After a layer of SWNTs was deposited, the Au electrodes were removed using the etchants I_2 and KI, and the Cr electrodes were removed using perchloric acid and ammonium nitrate, plus an organic wash. A second identical electrode pattern, oriented perpendicular to the first, was defined using optical lithography, followed by Cr/Au deposition using electron beam evaporation.

Single walled carbon nanotubes may be suspended into orthodichlorobenzene (ODCB) solution with only about 10 minutes of bath sonication. However, best results were achieved by sonicating for longer times (1 hour), so as to completely disperse the tubes into single strands. After sonication, if a drop of the SWNT/ODCB solution is spun coated onto a wafer, AFM imaging reveals that the vast majority of the tubes are either isolated SWNTs or small SWNT ropes.

A 1-5 milliliter (ml) aliquot of the SWNT/ODCB solution was then added to 100 ml of $CHCl_3$ to form solution 2. Solution 2 is successively diluted to a volume of 500 ml over a period of 1 hour, and under bath sonication. This process may be scaled down to less solvent, as long as the relative ratios of SWNT/ODCB/$CHCl_3$ are preserved.

Aligned SWNT devices

Several SWNT ropes, deposited using the above described conditions, were electrically interrogated to ascertain whether or not this type of deposition was selective for any particular types of nanotubes (metallic, insulating, etc.). As can be seen from Table Ap1., the deposition process apparently is not selective for tube (or rope) type, although we did observe that the process was more selective for tubes than for organic and inorganic contaminants that are co-dispersed with the SWNTs in the ODCB/$CHCl_3$ solution.

Table Ap1. SWNT rope structure/transport data collected from field-deposited tubes

Diameter (nanometers)	**Resistance**	**Comment**[a]
8 nm	0.5 megaOhm	Metallic
10 nm	0.5 megaOhm	Metallic
5-6 nm	42 megaOhm	Semiconducting[c]
4 nm	225 megaOhm	Semiconducting
3 nm	31 megaOhm	Semiconducting[c]
1-2 nm	173 megaOhm	Semiconducting
7.8 nm[b]	~0.5 megaOhm	Metallic
7.9 mm[b]	0.5 megaOhm	metallic
6.1 nm[b]	1 gigaOhm	Semiconducting
4.8 nm[b]	1 gigaOhm	Semiconducting
10 nm[b]	10 gigaOhm	Semiconducting

[a] The difference between metallic and semiconducting ropes was determined by monitoring conductivity while applying a voltage to the back side of the wafer as a gate. Generally, an ohmic (linear) current-voltage response was found for metallic, and a non-ohmic current voltage response for semiconducting.

[b] Denotes that a thicker (10 nm + 50 nm Au) titanium contact was deposited. These devices exhibited more stable current-voltage responses that was not likely limited by contact resistance. All other devices utilized a (5 nm + 50 nm Au thick) titanium contact

[c] Denotes that I-V curves were non-ohmic. However, the change in conduction by applying a voltage to the gate was minor.

Supplemental Details of the Calculations

The experimental parameters utilized for calculation of the crossbar pitch as a function of SWNT rope length were ε ($HCCl_3$)=4.8, T=300K, V_{ext}=0.0028 statvolts (V_{rms} is modified due to the curvature of the field close to the electrodes). The number density of tubes in solution was calculated from experimental parameters. In particular, we converted a 10^{-4} weight % in ODCB, taking an average nanotube length of 0.5 μm (with diameter 0.8 nm) ≈ 12 carbons/Å, and assuming additivity of volumes.

As discussed in the text, in order to obtain the electrostatic potential of the deposited tubes in the presence of surrounding counterions (ODCB) in a solvent with dielectric constant ε ($CHCl_3$), we use the linearized Poisson-Boltzmann (PB) equation. To obtain the screened Coulomb interaction in between the nanotubes, we followed standard simplifications. The Poisson-Boltzmann equation neglects correlations in the counterion distribution. Its linearization is rigorously justified only at weak potentials; however, it works well when the bare charge is suitably renormalized.[1] The linearized equation is consistent with our superposition of solutions, which is further justified in the case of weak overlap of ionic layers, as is mostly our case here. Finally, we consider the energy as a linear function of the charge.

In addition, we also made the approximation that the tubes were cyclindrical conductors – a result consistent with *ab initio* calculations on the screening of applied fields by nanotubes.[2] Not all tubes are metallic, but within a rope both semiconducting and metallic tubes are present. Since tubes are weakly coupled within a rope, we ignore here intricacies that may arise from inter-tube interactions and assume that the charge properties are dominated by the metallic tubes.

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[1] J.P. Hansen, H. Löwen, *Ann. Rev. Phys. Chem.* **2000**, 51**,** 209 - 242.
[2] L.X. Benedict *et al.*, Phys. Rev. B **1995**, 52, 8541-8549.

We adopted a description of the nanotubes in terms of a prolate ellipsoid with very highly anisotropic axes (a>>b=c). When the field is parallel to the main axis of the conducting cylinder, the polarizability is essentially infinite: $a_{//} = V / 4\pi n_{//}$,where the volume $V = 4\pi ab^2 / 3$ and $n^{//} \approx \frac{b^2}{a^2}[\log(2a/b) - 1)]$ [3]. Meanwhile, the polarizability in the transverse directions remains finite. The quantum mechanical calculation is fairly involved but the relevant physics remains qualitatively the same.

[3] L.D. Landau, E.M. Lifshitz, L.P. Pitaevskii, *Electrodynamics of Continuous Media*, Pergamon Press, Oxford, 1984