A ‘Bottom-up’ Redefinition for Mobility and the Effect of Poor Tube-Tube Contact on the Performance of CNT Nanobundle Thin Film Transistors

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Background: There have been many recent reports on Nanobundle Thin Film Transistors (NB-TFTs) based on percolating network of randomly-oriented Silicon nanowires (NW) and Carbon nanotubes (NT) or sticks in general (Fig. 1) with hopes of approaching mobility (\( \mu \)) of single CNT/NW transistors (\( \mu_L \)), without being limited by placement issues and low on current, \( I_{ON} \). High-\( \mu \) and highly homogenous NB-TFTs have potential to replace currently-dominant materials like amorphous (a-)Si or poly (p-) Si in applications in macroelectronics such as displays, e-paper, bio-chemical sensors, conformal radar, solar cells and others.1-4. Puzzling, however, is the fact that the reported values of \( \mu \) of NB-TFT (\( \mu_{NB} \)) – calculated by traditional ‘top-down’ effective media approach (EMA) -- is not only far poorer than single CNT transistors, but also appears to be a random function of experimental conditions.2,3,7,8. In this paper, we show that (a) the randomness of \( \mu_{NB} \) is not intrinsic, but rather signals the breakdown of ‘top-down’ definition \( \mu_{NB} \) and a percolation-theory based ‘bottom-up’ definition of \( \mu_{NB} \) can consistently interpret the results, and (b) the difference between \( \mu_{NB} \) and \( \mu_L \) can be attributed to geometrical parameters of transistor (like) such as tube density (\( D \)), tube length (\( L_S \)), channel length (\( L_C \)), etc. and tube-tube contact (\( C_g \)). Our results not only provide specific guidance to achieve geometry-specific theoretical limits of \( \mu_{NB} \), but also suggest simple characterization of technology-critical \( C_g \) from a few simple measurements.

Stick Percolation Model: We constructed a sophisticated first-principle numerical stick-percolation model for the above NB-TFTs by generalizing the random-network theory. The model randomly populates a 2D grid by sticks of fixed length (\( L_S \)) and random orientation (\( \theta \)) (Fig. 1) and determines \( I_{ON} \) through the network by solving the percolating electron transport through individual sticks. In contrast to classical percolation, the NB-TFT is a heterogeneous network: 1/3 of the CNTs are metallic and remaining 2/3 are semiconducting. Since, \( L_C \) and \( L_S \) are much larger than the phonon mean free path, linear-response transport (small \( V_{sd} \) and constant \( V_{gs} \) obviates the need to solve the Poisson equation explicitly) within individual stick segments of this random stick-network system is well described by drift-diffusion theory.1 The low bias drift-diffusion model to allow direct comparison of NB-TFT mobilities across different labs and with other competing technologies such as a-Si and p-Si. We have also suggested a simple experimental measure of the critical tube-tube contact parameter to allow design of optimized transistors. Conclusion: We have redefined the mobility for NB-TFTs from the ‘bottom-up’ perspective using the stick percolation model to allow direct comparison of NB-TFT mobilities across different labs and with other competing technologies such as a-Si and p-Si. We have also suggested a simple experimental measure of the critical tube-tube contact parameter to allow design of optimized transistors.

show the current dependence on to which each of the samples represent. The equations respectively. (a) (b) (c) (e) (f) (g) supported by the Network of Computational Prof. J. A. Rogers for helpful discussions. This work was the drain current).

Fig. 2: Normalized current distribution for network with high (a, b, c) and low (e, f, g) density for $L_C/L_S = 1, 2, 4$, respectively. (d) $I_{ON}$ vs. $L_C$ plot for various tube densities ($D$). The symbols show experimental data from Ref. [3] and the lines show the simulations using the stick percolation model. The arrows indicate the density and $L_C$ to which each of the samples represent. The equations show the current dependence on $L_C$ with appropriate current exponent, $m$. A common color bar for all the figures is also shown. The dashed arrows in (e, f, g) show the current paths.

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