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A “Bottom-Up” Redefinition for Mobility and the Effect of Poor Tube–Tube Contact on the Performance of CNT Nanonet Thin-Film Transistors

Ninad Pimparkar and Muhammad Ashraful Alam

Abstract—Nanonet thin-film transistors (NN-TFTs) based on random or aligned networks of single-wall carbon nanotubes are often regarded as a promising high-performance alternative to amorphous-Si technology for various macroelectronics applications involving sensors and displays. The comparison of NN-TFTs with other competing technologies such as organic, a-Si, and p-Si TFTs, however, has proved difficult as the mobility of these devices (counterintuitively) depends on a host of geometrical parameters such as tube density D , tube length L_S , channel length L_C , tube–tube contact C_{ij} , etc. In this letter, we redefine the mobility for NN-TFTs by generalizing the classical definition from a “bottom-up” perspective based on a stick percolation model. This new definition would allow a direct comparison of NN-TFT mobilities across different laboratories and with other competing technologies. We also suggest a simple experimental measure of the critical tube–tube contact C_{ij} parameter to allow design of optimized transistors.

Index Terms—Carbon nanotube (CNT), inhomogeneous percolation theory, mobility redefinition, network transistor, thin-film transistor (TFT), tube–tube contact.

I. INTRODUCTION

THERE have been many recent reports on nanonet thin-film transistors (NN-TFTs) based on percolating network silicon nanowires (NWs) and carbon nanotubes (CNTs) (or sticks in general; Fig. 1) with hopes of approaching mobility μ of single CNT/NW transistors (μ_1), without being limited by the challenge of self-aligned placement of single tubes. High- μ and highly homogenous NN-TFTs have potential to replace currently dominant materials like amorphous Si (a-Si) or poly-Si (p-Si) in applications in macroelectronics such as displays, e-paper, biochemical sensors, conformal radar, solar cells, and others [1]–[4]. Puzzling, however, is the fact that the reported values of μ of NN-TFT (μ_{NN})—calculated by a traditional “top-down” effective media approach—are not only far poorer than single CNT transistors but also appear to be a random function of experimental conditions [3], [5], [6]. In this letter, we show the following: 1) that the random is not process related, but rather signals the breakdown of a “top-down”

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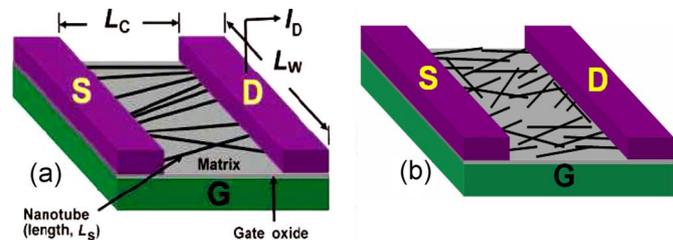


Fig. 1. Schematics of NN-TFTs with (a) short channel ($L_C < L_S$; nanosticks directly bridge the source S and the drain D) and (b) long channel ($L_C > L_S$; electrons must percolate through the nanostick network to contribute to the drain current). L_C is the channel length, L_W is the channel width, and L_S is the stick length; S, D, and G are the source, drain, and gate electrodes, respectively.

definition and that a percolation-theory-based “bottom-up” definition of μ_{NN} can consistently interpret the results and 2) that the difference between μ_1 and μ_{NN} can be attributed to geometrical parameters of transistor such as areal tube density D , tube length L_S , channel length L_C , tube–tube contact parameter C_{ij} , etc. Our results not only provide specific guidance to achieve geometry-specific theoretical limits of μ_{NN} but also suggest simple characterization of the technology-critical C_{ij} parameter by simple measurements.

II. STICK PERCOLATION MODEL

We constructed a first-principle numerical stick percolation model for NN-TFTs by generalizing the random network theory. The model [2] randomly populates a 2-D grid by sticks of fixed length L_S and random orientation θ (Fig. 1) and determines the ON-current I_D through the network by solving the percolating electron transport through individual sticks. In contrast to classical percolation, the NN-TFT is a heterogeneous network: one third of the CNTs are metallic, and the remaining are semiconducting. Since L_C and L_S are much larger than the phonon mean-free path, the linear-response transport (a small V_{SD} and a constant V_G obviate the need to explicitly solve the Poisson equation) within individual stick segments of this random stick–network system is well described by the drift–diffusion theory [2]. The low-bias drift–diffusion equation $J = q\mu n d\varphi/ds$ when combined with the current continuity equation $dJ/ds = 0$ gives the nondimensional potential φ_i along tube i as $d^2\varphi/ds^2 - C_{ij}(\varphi_i - \varphi_j) = 0$. Note that s is the length along the tube, $C_{ij} = G_0/G_1$ is the dimensionless charge-transfer coefficient between tubes i and j at their intersection point, and G_0 [7] and $G_1 (= qn\mu/\Delta x)$ [2]

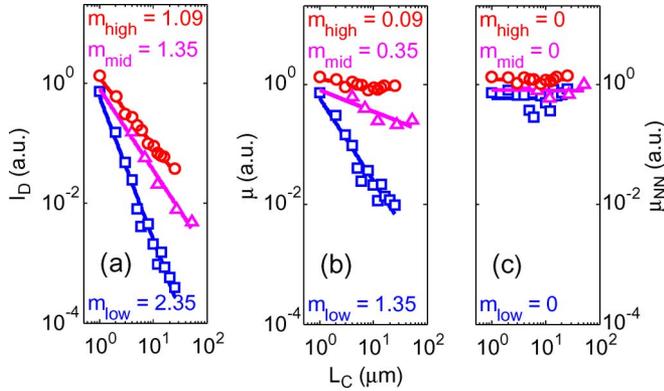


Fig. 2. (a) Experimental I_D versus L_C plot for (red) high-density [3], (magenta) medium-density [1], and low (blue) density random network for long channel transistor, i.e., $L_C > L_S$. The current exponent given by the slope of the lines are given by $m = 1.09$, 1.35 , and 2.35 , respectively. The experimental data have been normalized to highlight and compare the slopes of the I_D - L_C curves. (b) μ versus L_C plot for the networks in (a) using the conventional definition of mobility. The mobility is dependent on the channel length with exponents $m = 0.09$, 0.35 , and 1.35 , respectively. (c) NN-TFT mobility versus L_C from the “bottom-up” perspective. Note that this mobility is independent of L_C .

are the mutual conductance and self-conductance of the tubes, respectively. Here, n is the carrier density, μ is the mobility, and Δx is the grid spacing. The stick percolation networks are the nonclassical 2-D conductor and satisfy the following finite-size scaling relationship [8], [9]:

$$I_D \sim k(V_G, V_D) \times \xi \left(\frac{L_S}{L_C}, DL_S^2 \right) \\ = C_{\text{OX}} L_W (V_G - V_{\text{TH}}) V_D \frac{1}{L_S} \left(\frac{L_S}{L_C} \right)^{m(DL_S^2)}. \quad (1)$$

Here, k is a material-specific bias-dependent constant, and the scaling exponent $m(DL_S^2)$ is a universal constant that depends *only* on the areal tube density D and stick length L_S , as shown in Fig. 2(a). For transistors in the linear-response regime, the constant $k = C_{\text{OX}} L_W V_D (V_G - V_{\text{TH}})$, where C_{OX} is the gate capacitance, L_W is the channel width, and V_D , V_G , and V_{TH} are the drain, gate, and threshold voltages of the transistor, respectively.

III. RESULTS AND DISCUSSION

We now use the aforementioned model to resolve the two puzzles of μ_{NN} .

A. Randomness of Long-Channel μ_{NN}

Fig. 2(a) shows the dependence of I_D on the device parameters L_C and D and allows us to calculate—through (1)—the scaling exponent m given by the slope of the I_D - L_C curves. For classical single crystalline transistors, I_D is inversely proportional to L_C or, equivalently, directly proportional to the channel conductance. In general, this simple textbook rule does not apply to NN-TFTs. For large D , almost all the sticks participate in source/drain (S/D) conduction, and the NN-TFT behaves similar to Si-TFT, i.e., $m \sim 1$ [Fig. 2(a), red curve; (1)]. For lower density NN-TFTs at long-channel lengths, however,

only a fraction of the sticks participate in S/D conduction, and there are islands or pools of nanosticks that do not connect the source and the drain. These unconnected islands of sticks form newer paths between the source and the drain as the channel length is reduced, and the drain current superlinearly increases with reduction in L_C , i.e., the conduction is defined by $m > 1$, as shown by the blue and magenta curves in Fig. 2(a).

In the literature, however, researchers universally use the “top-down” definition of

$$\mu \sim \frac{dI_D}{dV_G} \frac{1}{V_D} \frac{L_C}{L_W C_{\text{OX}}} \quad (2a)$$

to characterize NN-TFTs [Fig. 2(b)]. Such definition of μ presumes that $I_D \propto 1/L_C$ [i.e., $m = 1$ in (1)], and its uncritical use in percolating systems like organic TFTs or NN-TFTs results in (unphysical) geometry-dependent mobility that appears to reduce with lower D and longer L_C (Fig. 2(b), blue squares). Given these counterintuitive dependences on geometrical parameters, it becomes nearly impossible to compare the qualities of films reported by different laboratories. Instead of the classical definition, therefore, one should redefine μ from a “bottom-up” perspective based on (1) by requiring that $I_D \sim \mu_{\text{NN}}/L_C$, such that

$$\mu_{\text{NN}} \sim \frac{dI_D}{dV_G} \frac{1}{V_D} \frac{L_S}{(L_S/L_C)^m} \frac{1}{L_W C_{\text{OX}}}. \quad (2b)$$

This definition accounts for the scaling exponent m for the drain current and provides a device-geometry-independent value for the mobility. The new definition allows a comparison among mobility values reported from different laboratories [3], [5], [6], [10], as shown in Fig. 2(b) and (c). Not surprisingly, for high-density networks (Fig. 2, red circles), with $m \sim 1$, both definitions [(2a) and (2b)] give the same result, i.e., $\mu \sim \mu_{\text{NN}}$. In other words, as the network approaches a continuous thin-film limit regardless of the device geometry, their respective mobilities begin to converge, as expected.

B. Role of C_{ij} in Short- and Long-Channel Transistors

The second puzzle is that experiments often show that the μ_{NN} of a long-channel ($L_C > L_S$) NN-TFT is almost an order of magnitude smaller than that of a short-channel ($L_C < L_S$) transistor [1], [3], [4]. In long-channel transistors, electrons must percolate from one stick to next through the junctions (characterized by C_{ij}), whereas for short-channel transistors, the tubes directly bridge the source and the drain [1], [3], [11]. Hence, we need to reanalyze the role of *imperfect* C_{ij} (poor tube-tube transfer resistance) to explore differences between short- and long- L_C transistors. Fig. 3(a)–(c) shows the simulated I_D versus L_C for short- and long-channel NN-TFTs for high and low values of C_{ij} . Note the increasingly abrupt reduction in I_D at $L_C/L_S \sim 1$ with reduction in C_{ij} [Fig. 3(a)–(c)]. Fig. 3(e) plots the magnitude of the abrupt drop in current R_{ij} at the transition point $L_S/L_C \sim 1$ as a function of C_{ij} for different tube densities D . This plot shows that $R_{ij} \propto C_{ij}$ for low values of C_{ij} or for poor tube-tube contact [Fig. 3(b) and (c)] but saturates to 1, as expected, for higher C_{ij} [Fig. 3(a)] or for

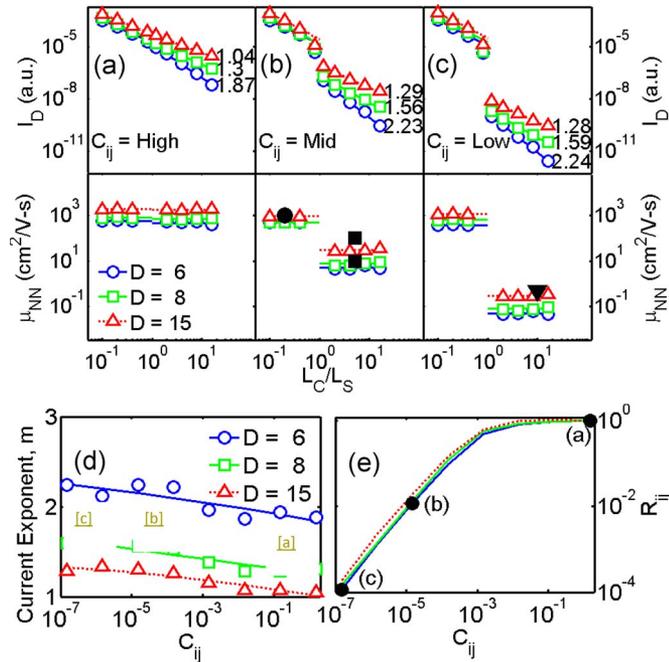


Fig. 3. Simulated I_D versus L_C/L_S plot with (a) high, (b) medium, and (c) low tube-tube contact parameter C_{ij} . The lower panel shows the corresponding mobilities μ_{NN} . The black symbols in the lower panels of (a)–(c) map the reported mobility values from various laboratories with a filled circle [1], filled squares [3], and a filled inverted triangle [4]. For these simulations, the tube length L_S is kept constant, but the tube density D is varied. Note the abrupt transition in (b) and (c) at $L_S/L_C = 1$, which is a result of the imperfect tube-tube contact. (d) Current exponent m versus C_{ij} for different density tube networks. The exponents are relatively insensitive to the tube-tube contact. (e) Normalized drop in current R_{ij} at the transition point $L_C/L_S = 1$. Here, R_{ij} is the ratio of current I_D for $L_C/L_S \sim 1^+$ and $L_C/L_S \sim 1^-$. The ratio R_{ij} is insensitive to the tube density D . The dark circles correspond to (a)–(c), as indicated.

good tube-tube contact. Finally, Fig. 3(d) plots the exponent m (see also Fig. 2) for different densities as a function of C_{ij} . m monotonically increases with decreasing C_{ij} , as the relative contribution of the tube-tube resistance to the total device resistance goes up, and the transport begins to be dominated by the transfer resistance at the tube-tube junction. The ratio of mobilities μ_{NN} for short- ($L_C > L_S$) and long- ($L_C < L_S$) channel NN-TFTs can directly be related to C_{ij} using Fig. 3(e), resolving the previously discussed puzzle. Moreover, once D is determined from SEM images [1], [6] and m from Fig. 2, C_{ij} can also be read out from Fig. 3(d), thus providing an experimental measure of a technology-critical parameter for the design of NN-TFTs.

IV. CONCLUSION

We have redefined the mobility for NN-TFTs from the “bottom-up” perspective using the stick percolation model to allow a direct comparison of NN-TFT mobilities across different laboratories [3], [5], [6] 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 the design of optimized transistors.

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