The Origins and Characteristics of the Threshold Voltage Variability of Quasi-Ballistic Single-Walled Carbon Nanotube Field-Effect Transistors

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Supplementary Fig. 1. Subthreshold transfer characteristics for sets of FETs made on SWNTs with (part a) and without (part b) annealing and nitric acid washing after deposition.

Supplementary Fig. 2. (a) Large area atomic-force microscopy (AFM) image of individual SWNTs randomly deposited on top of SiO₂/Si wafer by drop casting for diameter measurement. (b) Histogram showing the diameter distribution of sorted semiconducting SWNTs measured by AFM. The black solid line is Gaussian fit to the data. (c) Absorption spectrum of sorted SWNT solution used in the experiment showing the second van Hove transition for semiconducting SWNTs. The black solid line is Gaussian fit to the data.

Supplementary Fig. 3. Transfer characteristics of a collection of the same 24 SWNT FETs with L of 100 nm fabricated on 10 nm SiO_2/Si substrate in logarithmic scale as measured in air (part a), in vacuum after 400 K anneal (part b), and at 20 K in vacuum (part c), respectively. Applied V_{DS} is -0.05 V.

Supplementary Note 1: Diameter distribution of carbon nanotubes. The diameter distribution of the nanotube source we used, which is high purity solution-processed semiconducting nanotubes sorted in house by the size-exclusion chromatography method,¹ is firstly measured directly using AFM. Here individual nanotubes are randomly deposited by drop casting on a flat wafer surface as shown in Figure S-1a, with the diameter (d) of each SWNT measured by AFM and plotted in Figure S-1b. A Gaussian-type diameter distribution with a mean of 1.2 nm and a standard deviation of 0.3 nm is observed. To make sure that the distribution measured by AFM really represents the bulk distribution, the nanotube diameter distribution is further evaluated using absorption spectroscopy. There is a simple relationship between d and the energy of the optical interband transitions of SWNTs.² More specifically, the energy of the second van Hove transition for semiconducting SWNTs (E_{22}^S) is given by

$$E_{22}^S = 4a_0\gamma_0 / d , \quad (s1)$$

where $a_0=1.42 \text{ \AA}$ is the carbon-carbon bond length, and $\gamma_0=2.7$ is the nearest neighbor overlap integral.^{3, 4} By fitting the measured bulk absorption peak of SWNTs with a Gaussian curve after baseline subtraction as illustrated in Figure S-1c, we can obtain the average and the standard deviation of the wavelength, which translates into a d of $1.2\pm0.3 \text{ nm}$ according to eq. (s1). These numbers are in good agreement with the AFM result. Such narrow diameter distribution is typical of solution processed SWNTs synthesized by the arc-discharge method, while SWNTs grown by chemical vapor deposition generally demonstrate a much larger diameter variation.⁵

Supplementary Note 2: Error bar calculation for the Pelgrom plot. Since $L_{ch}=L/\sin\theta$, average L_{ch} for randomly positioned SWNTs can be approximately calculated for the range of L_{ch} studied in this paper,

$$\overline{L_{ch}} = \frac{L}{\sin\theta} = \frac{L}{\int_0^\pi \frac{\sin\theta}{\pi/d\theta}} = \frac{\pi L}{2}. \quad (1)$$

The standard deviation of $\sqrt{W_{eff} \cdot L_{ch}}$ can be derived as,

$$\sigma^2\left(\frac{1}{\sqrt{\Lambda \cdot t_{ox} \cdot L_{ch}}}\right) = \left[\frac{\overline{\Lambda \cdot t_{ox}}}{2(\overline{\Lambda \cdot t_{ox} \cdot L_{ch}})^{3/2}} \cdot \sigma(L_{ch})\right]^2 + \left[\frac{\overline{t_{ox} \cdot L_{ch}}}{2(\overline{\Lambda \cdot t_{ox} \cdot L_{ch}})^{3/2}} \cdot \sigma(\Lambda)\right]^2 + \left[\frac{\overline{\Lambda \cdot L_{ch}}}{2(\overline{\Lambda \cdot t_{ox} \cdot L_{ch}})^{3/2}} \cdot \sigma(t_{ox})\right]^2, \quad (2)$$

where $\sigma(L_{ch})$ is calculated according to

$$\sigma^2(L_{ch}) = \left[\frac{1}{\sin\theta} \sigma(L)\right]^2 + \left[\frac{-L}{\sin^2\theta} \sigma(\sin\theta)\right]^2. \quad (3)$$

$\sigma(L)$ is about 2 nm as measured by scanning electron microscopy (SEM), and $\sigma(\sin\theta)$ is given by,

$$\sigma^2(\sin\theta) = \int_0^\pi \frac{(\sin\theta - 2/\pi)^2}{\pi/d\theta} = \frac{1}{2} - \frac{4}{\pi^2}. \quad (3)$$

$\sigma(t_{ox})$ is about 0.2 nm as measured by ellipsometry.

Reference

1. Tulevski, G. S.; Franklin, A. D.; Afzali, A., High Purity Isolation and Quantification of Semiconducting Carbon Nanotubes *via* Column Chromatography. *ACS Nano* **2013**, *7*, 2971-2976.
2. Odom, T. W.; Huang, J.-L.; Kim, P.; Lieber, C. M., Structure and Electronic Properties of Carbon Nanotubes. *J. Phys. Chem. B* **2000**, *104*, 2794-2809.
3. Saito, R.; Dresselhaus, G.; Dresselhaus, M. S., Trigonal Warping Effect of Carbon Nanotubes. *Phys. Rev. B* **2000**, *61*, 2981-2990.
4. Correa, J. D.; da Silva, A. J. R.; Pacheco, M., Tight-Binding Model for Carbon Nanotubes from *ab initio* Calculations. *J. Phys.: Condens. Matter* **2010**, *22*, 275503.
5. Liu, X.; Pichler, T.; Knupfer, M.; Golden, M. S.; Fink, J.; Kataura, H.; Achiba, Y., Detailed Analysis of the Mean Diameter and Diameter Distribution of Single-Wall Carbon Nanotubes from Their Optical Response. *Phys. Rev. B* **2002**, *66*, 045411.