Development of Carbon Nanotube Field-Effect Transistors for Use in Next Generation Electronics

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Abstract:

Due to its exceptional electronic properties, the carbon nanotube field-effect transistor (CNTFET) is a promising alternative to the traditional metal-oxide-semiconductor field-effect transistor (MOSFET) used in current devices, replacing the channel material in MOSFETs with thin carbon nanotubes with diameters of 1-2 nm. Because various difficulties have arisen in the mass production of reliable CNTFETs, this project aimed to fabricate and analyze the efficiency of a number of these devices, examining the viability of their optimization for industrial applications. Spinning solutions that were specifically sorted for a high concentration of semiconducting CNTs onto silicon substrates, we then located these tubes on an atomic force microscope (AFM). The devices were manufactured through electron beam (e-beam) lithography and deposition. We applied test voltages between the source and drain of these devices and observed the amount of current flowing through the channels with respect to the backgate voltage. Insights gained as a result of these experiments will have a significant impact on the performance and power of future electronic devices.

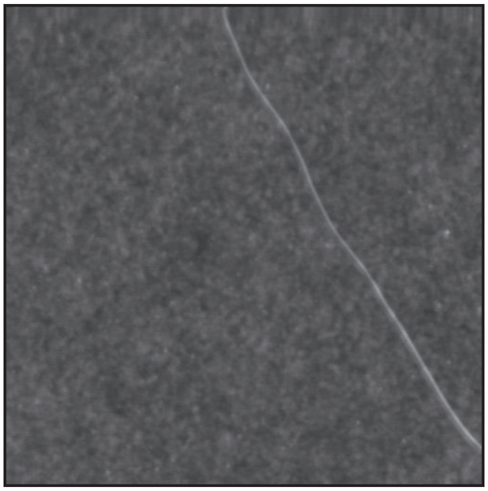

Figure 1: 1 µm × 1 µm image of a carbon nanotube as seen under an AFM.

Introduction:

For more than 40 years, Moore's Law has held true in that the number of transistors on a chip doubles approximately every two years. However, an increase in the transistor count must lead to a decrease in transistor size, and serious limitations of current fabrication technology are faced at the sub-22 nm range. Since Intel, a world leader in the semiconductor industry, has already begun processing at the 32 nm scale in 2010, the success of predictions made by Moore's Law may soon reach an end. CNTFETs provide a possible alternative in that they have near ballistic transport (minimal electron scattering) and much higher electron mobility than silicon (up to 70 times) [1]. However, challenges in their fabrication still exist, which includes the separation of metallic and semiconducting nanotubes in the same mixture and having a wide range of diameter in CNTs found in the mixture, which affects their electronic properties.

Figure 2: Image of actual device as seen under a probe station.

The Shinohara group from Japan has been working on a separation method known as multicolumn gel chromatography. This method is based on the structure dependent interaction strength of CNTs with an allyl dextran based gel. There are multiple columns of gel and the CNT solution is dispersed (using a surfactant called SDS) on the top of the first column. The absorption site at this column is fully occupied by nanotubes that exhibit the strongest interaction with the gel and the rest of the solution moves on to the next column. Metallic nanotubes are collected at the end because they exhibit the lowest interaction with the gel [2]. Since transistors need to constantly switch between the on and off state, semiconducting CNTs are desired.

In our project, we examined the viability of multicolumn gel chromatography through CNTFET fabrication using a pre-sorted solution prepared by the Shinohara group using the above method.

Procedure:

We began the fabrication process by placing cross-shaped markers on silicon wafers through optical lithography. A sorted solution of CNTs was then spun onto the silicon substrate. Individual CNTs were located using an AFM, and Figure 1 shows a zoomed-in view of one such tube. The actual devices were manufactured through e-beam lithography and deposition, and one such device is shown in Figure 2. Afterwards, the devices were tested under a probe station to observe on/off ratio and on-current through the CNT channel.

Results and Discussion:

Due to time constraint, only devices fabricated from eight CNTs were fully tested, and of those, two were found to be nonfunctioning. The on/off ratio we observed was comparable to previous experimental data, but the on-current was not. Figure 3 shows a plot of the CNT diameter versus on-current.

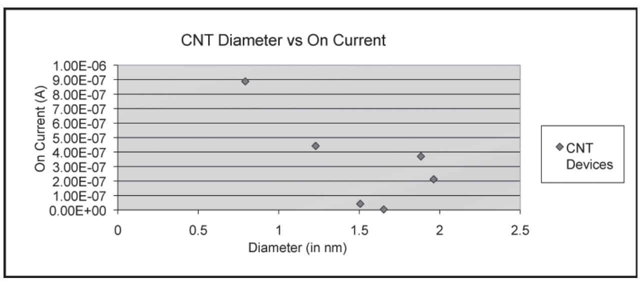

Figure 3: Our experimental data for sorted CNTs.

Device	Diameter	On Current (-0.5 V)	On/Off Ratio
D01-2	1.652nm	4.04E-09A	2.83E+03
E02-1	1.506nm	4.24E-08A	2.64E+02
D01-1	1.962nm	2.12E-07A	8.48E+02
D03-2	1.883nm	3.70E-07A	8.24E+03
E01-1	1.229nm	4.42E-07A	7.32E+02
A-2	0.792nm	8.88E-07A	6.75E+03

(Devices ranked by on current from lowest to highest)

Figure 4: Summary of working devices (6/8 tested).

Theoretically, a larger diameter should allow for higher current flow, but our results indicate the highest on-current was measured from a device with the smallest CNT diameter. Also, we expected the on-current to be at least 5 μA, but the highest we achieved with our devices was only 0.9 μA [3]. A data summary of the working devices can be found in Figure 4.

Conclusion and Future Work:

The on/off ratio that devices typically demonstrated suggests that the solution was well sorted and the tubes were semi-conducting (numerical accuracy was limited by probe station). However, our experimental results for on-current do not match with previously reported data, so we will need to test more devices to confirm the viability of our process flow (including gel chromatography) and improve the on-current data. For future work, we aim to achieve comparable on-current from CNTs of similar diameters. Other than testing more devices, we will try to improve the contact resistance between the CNT and electrode. This could be done by better cleaning of SDS (a surfactant used in dispersing CNTs), using a metal other than palladium such as rhodium, and doping via plasma treatment prior to deposition.

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