Investigation of Electron Transport in Functionalized Carbon Nanotubes

Mark Brunson
Mechanical Engineering, San Francisco State University

NNIN iREU Site: Institut Für Bio- Und Nanosysteme (IBN), Forschungszentrum, Jülich, Germany
NNIN iREU Principal Investigator: Dr. Carola Meyer, Peter Grünberg Institute 6, Forschungszentrum Jülich
NNIN iREU Mentor: Robert Frielinghaus, Peter Grünberg Institute 6, Forschungszentrum Jülich
Contact: m.brunson@me.com, c.meyer@fz-juelich.de, r.frielinghaus@fz-juelich.de

Introduction:

Since the discovery of carbon nanotubes (CNTs), they have shown potential for use in applications that benefit from their mechanical or electrical properties. CNTs are hollow cylinders of graphene sheets, which can consist of one or more walls depending on the growth parameters. They can be metallic or semiconducting.

One advantage of CNTs is the ability to tune properties by functionalizing them with various molecules. In this work, characterization of CNTs functionalized with tailor-made Mn_4 molecules was performed. These manganese molecules were single molecular magnets, which allowed for control of the spintronic properties of CNT devices. Oxidizing the CNTs introduced binding sites to the surface for the carboxylate groups of Mn_4 clusters to bond.

Experimental Procedure:

CNTs were synthesized on silicon (Si) substrates using a chemical vapor deposition (CVD) process. Ferritin was used as a catalyst; it was deposited onto the Si/SiO_2 substrate and heated in air to 450°C in order to remove the protein surrounding the iron core. The sample was then placed in a quartz tube of a tube furnace, purged in argon, and heated to 850°C. Upon reduction in 1.0 slpm hydrogen, CNTs were synthesized for 10 minutes with 0.52 slpm methane and 0.7 slpm hydrogen. The sample was finally cooled to room temperature in argon.

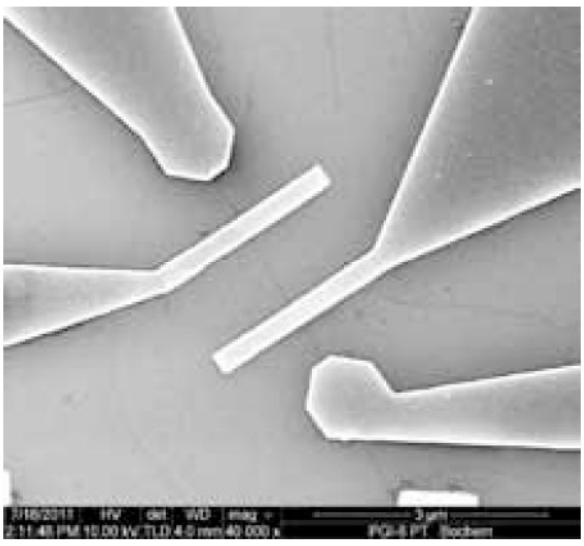

Figure 1: Image of a typical device obtained by scanning electron microscopy (SEM). Each nanotube is contacted by four isolated contacts.

In order to fabricate the device, a marker structure and bonding pads were written using electron beam (e-beam) lithography with 5 nm titanium and 60 nm gold for the structures. Sufficiently long and isolated CNTs were located using atomic force microscopy (AFM) and four-point contacts were designed. The contacts were written using the same lithography process: this time with 3 nm chromium and 60 nm palladium contacts to reduce contact resistance. An example of a typical device is shown in Figure 1. Since this sample was destroyed during the oxidation process for functionalization, a similar sample, which was instead made with titanium and gold contacts, was measured.

A three-point probe station was used to identify working devices by measuring both the bias sweeps and gate sweeps. These measurements also indicate the type of nanotube: semiconducting or metallic. A dilution refrigerator was used to observe the Coulomb blockade effect in a single nanotube, which behaves as a quantum dot. Once cooled to 70 mK, a dual sweep was performed such that there was a bias sweep of ± 4 mV for each gate voltage measured. Since a new matrix box was fabricated to reduce the cable length connecting the sample and the transducer, the new measurement setup required testing.

Results and Conclusions:

Though the CNTs were spread out with a slightly higher than optimal density, the sample was nevertheless processed. However, due to poor liftoff, gate leakage was evident in

all but two regions. Transport measurements were then performed so that influence from the chemical treatment could be quantified. In the electrical measurements at room temperature, the CNTs were all observed to be metallic, though mechanical strain suppressed the current in some cases. Resistances of ohmic nanotubes ranged from 80 kΩ to 1.4 MΩ.

In order to prepare the sample for functionalization, oxidation was performed by heating up the sample in air to 450°C. After oxidation, none of the previously working devices were still functional. However, the resistivity of the palladium was unchanged. It is possible that the contact resistance has greatly increased due to the difference of the coefficients of thermal expansion of the three present materials: gold, chromium, and palladium. Attempts to reduce the sample at 450°C in hydrogen were unsuccessful.

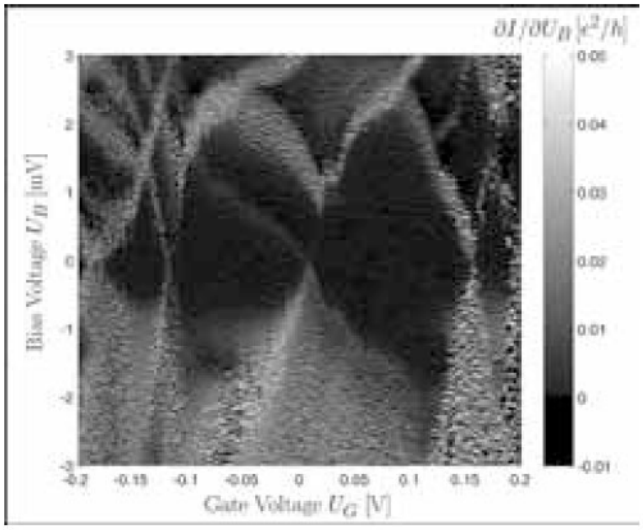

Figure 2: Measurement of the Coulomb blockade structure shows excited states as extra lines parallel to the topsides of the diamonds. Regions of negative differential conductance are also observed.

In order to test the optimized setup for the dilution refrigerator, a dual sweep was performed to obtain the Coulomb diamond structure of a CNT device. The diamonds, shown in Figure 2, are well defined, showing multiple excited states and regions of negative differential conductance. Coulomb peaks can be seen where the diamond points meet. The lever arm, α_G, was determined to be 0.0014. Using this information, the Coulomb peaks can be fit to determine the electron temperature [1]. From the peaks with the least disorder, the electron temperature is found to be 157 mK, as shown in Figure 3. This result was expected since the lattice temperature is 70 mK. This measurement shows that

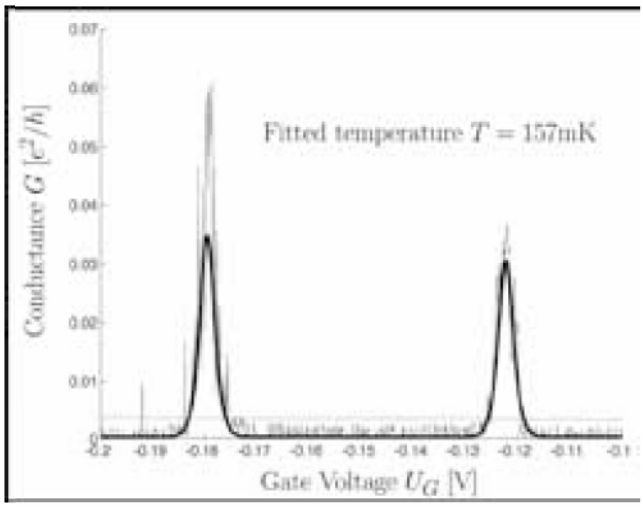

Figure 3: Coulomb peaks are fitted using the values obtained from the measured Coulomb blockade to determine the electron temperature.

the dilution refrigerator has in fact been optimized and is prepared for the necessary experiments with functionalized CNTs.

Future Work:

The effects of functionalizing CNTs with the manganese molecule clusters still need to be observed. After these measurements have been successfully performed, the manganese can be substituted in the cluster with other metals. Compounds with various magnetic properties will be bonded to the CNTs making it possible to observe the coupling of the CNT electronic system to the molecular magnets.

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References:

[1] Fuhrer, A., Fasth, C.; "Coulomb Blockade in Quantum Dots"; Lecture Notes, 23 April 2007.