



## One Dimensional Transport in Carbon Nanotubes

Paul L. McEuen, Marc Bockrath, David H. Cobden, and Jia G. Lu

Materials Sciences Division, Lawrence Berkeley National Laboratory and  
Department of Physics, University of California at Berkeley  
M/S 2-200 LBNL, Berkeley, CA 94720

Single-walled carbon nanotubes – nanometer diameter graphene cylinders – are a new class of one-dimensional (1D) conductors. Recent STM[1] and transport[2-8] experiments have shown that these tubes can be either semiconductors or 1D metals. Here we review our group's recent electrical studies[3-5] of these novel 1D conductors.

### 1. SAMPLE FABRICATION AND MEASUREMENTS

The devices used in these studies consist of individual single-walled nanotubes (SWNTs) or SWNT ropes[9] to which electrical contacts are made, as shown in Figure 1. The nanotubes are deposited onto  $SiO_2$  grown on top of a degenerately doped  $Si$  wafer. Atomic force microscope (AFM) imaging reveals that the diameters of the deposited objects vary between 1 and 10 nm, with the smallest ones being single SWNTs and the larger ones SWNT ropes.

Two methods are used to attach leads to a tube/rope. In the first method[3], a single tube/rope is located relative to prefabricated gold alignment marks using an AFM. Chromium-gold contacts are then deposited on top of the tube/rope using electron beam lithography and lift-off. In the second method[2], electron beam lithography is first used to define leads, and tubes/ropes are subsequently deposited on top of the leads.

In addition to the electrical contacts, the degenerately doped silicon substrate can be used as a gate electrode to adjust the charge per unit length of the tube/rope. Measurements of these devices can reveal either metallic[2-6] or semiconducting[7] behavior as a function of the gate voltage  $V_g$ . Here, however, we concentrate on results from metallic tubes.

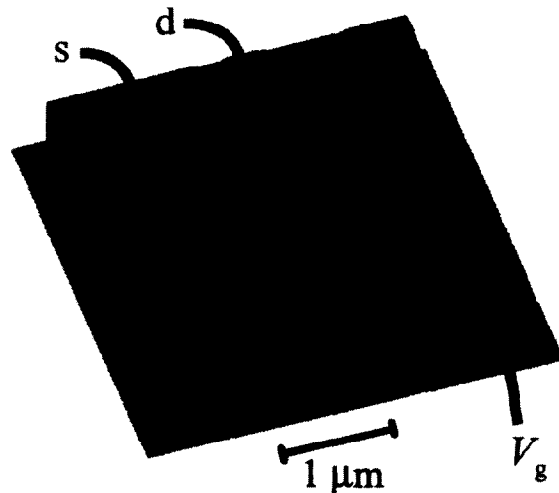


Figure 1. Single nanotube rope with electrical contacts.

Figure 2 shows the two-terminal conductance,  $G$ , versus gate voltage,  $V_g$ , for a rope contacted by the second technique. At low temperatures, a series of Coulomb oscillations are seen. The nanotube is thus acting as a 1D quantum dot for electrons [2-3], with a peak occurring each time an electron is added to the tube. Measurements in this regime are discussed in Section 2.

At higher  $T$ , the Coulomb oscillations are completely washed out and  $G$  is independent of  $V_g$ . A plot of  $G$  vs.  $T$  in this regime is shown in the inset to Figure 2. A steady increase in  $G$  is observed with increasing  $T$ , unlike the behavior expected for an ordinary metal. The origin of this behavior is discussed in Section 3.

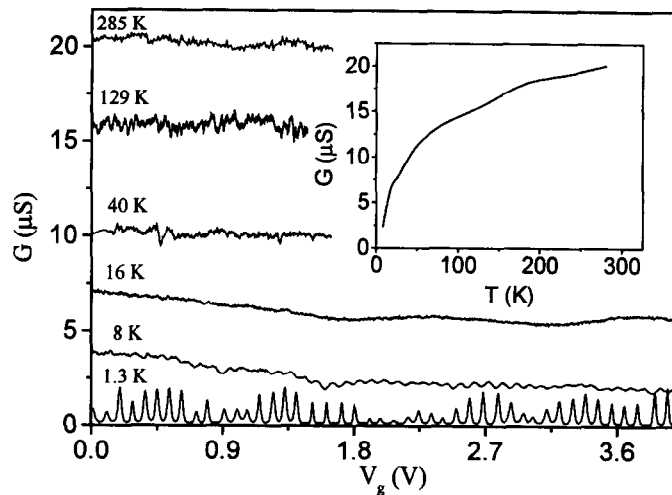


Figure 2.  $G$  vs.  $V_g$  for a nanotube device at different temperatures. At low  $T$ , Coulomb oscillations are observed. At high  $T$ ,  $G$  grows with  $T$ , as is seen in the inset.

## 2. 1D QUANTUM DOTS - LEVEL SPACINGS AND SPIN STATES

From detailed studies of the quantum dot behavior at low  $T$ , much can be learned about the properties of SWNTs and the effects of the electrodes on their properties. First, since the nanotubes show Coulomb oscillations at low temperatures, we infer that the electrodes only make tunneling contact to the tubes. The reason that this occurs is poorly understood at present.

From the measured charging energy of the device and simple estimates of the capacitance, we can also infer the length of the nanotube segment to which the electrons are confined. For devices made by the first technique, where the electrodes are patterned on top of the rope, we find that the electrons are confined to the length of rope between the leads[2]. This implies that the leads cut the nanotubes into segments. For samples created using the second technique, where tubes are deposited on top of leads, we find that the dot is often significantly larger than the lead spacing. This is in agreement with observations of the DELFT group[3]. In this case, the length of the dot is typically set by the length of the nanotube. This second contacting technique is clearly less invasive, but even it sometimes results in breaking

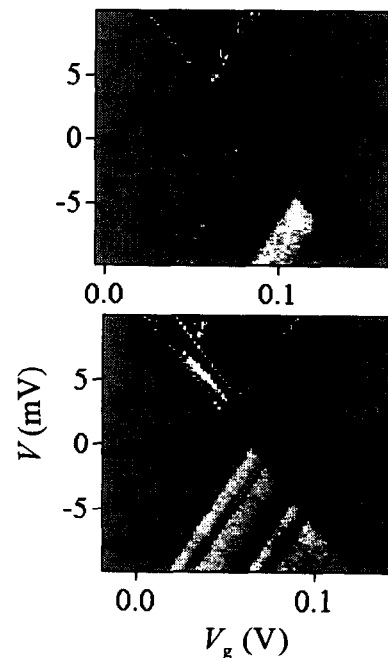


Figure 3. Greyscale plot of  $dI/dV$  vs.  $V_g$  and  $V$  at different magnetic fields.

up the tube into a series of dots.[8]

Measurements of the differential conductance can be used to perform excited-state spectroscopy of the electronic states, as is well known from studies of semiconductor dots.[10] Measurements on a short ( $L \sim 200$  nm) nanotube segment are shown in Figure 3. The lines seen in the figure correspond to tunneling through the ground and excited states of the nanotube dot. The spacing between the excited states is consistent with expectations for electrons confined to a 1D box.[2-4]

Other properties of the level spectrum can also be probed. To examine the spin state of the nanotube, we apply a magnetic field along the axis of the nanotube rope and examine the Zeeman splitting. From the pattern of the spin splitting, we conclude that as successive electrons are added the ground state spin oscillates between  $S_0$  and  $S_0+1/2$ , where  $S_0$  is most likely zero.[4] These results indicate that electrons in the tube do not spontaneously polarize due to the exchange interaction. This is in agreement with theoretical expectations[11] but in apparent disagreement with experiments by the DELFT group.[7]

### 3. TUNNELING INTO A TUBE – LUTTINGER LIQUID BEHAVIOR

We now turn to measurements at higher energies where the effects of charging and energy level quantization are relatively unimportant. Figure 4 shows the measured differential conductance of a device as a function of the applied bias  $V$ . At low biases,  $dI/dV$  is a constant that depends upon  $T$ . At high biases  $dI/dV$  increases with increasing  $V$ . Since the curve is roughly linear on a log-log plot, it implies that the differential conductance is well described by a power law,  $dI/dV \sim V^\alpha$ , where  $\alpha = 0.36$ . At the lowest temperature  $T=1.6$  K, this power law behavior occurs over two decades in  $V$ , from  $1 \text{ mV} < V < 100 \text{ mV}$ .

This behavior is in agreement with predictions for tunneling into a Luttinger liquid [12-13]. A Luttinger liquid is a 1D correlated many-body state whose low-energy excitations are plasmons. The electron interactions make it difficult to tunnel into the liquid and lead to a power-law variation of  $G$  with  $T$  at small biases ( $eV \ll k_B T$ ):

$$G(T) \sim AT^\alpha$$

or with  $V$  at large biases ( $eV \gg k_B T$ ):

$$dI/dV \sim V^\alpha.$$

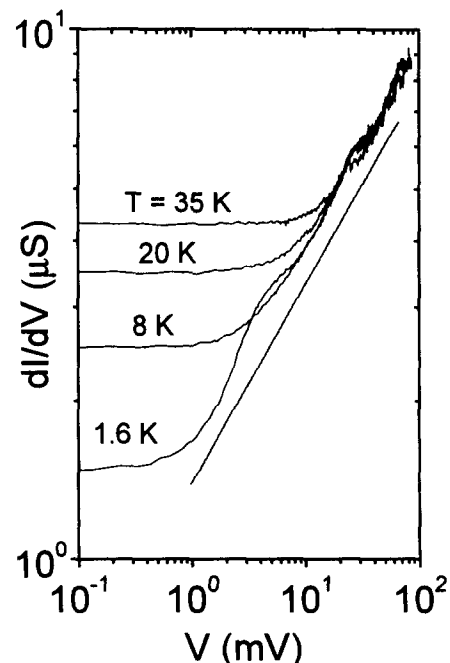


Figure 4.  $dI/dV$  vs.  $V$  at different temperatures, plotted on a log-log scale. Power law behavior versus  $V$  is observed.

The approximate power-law behavior versus  $T$  and  $V$  seen in the inset to Figure 2 and in Figure 4 are consistent with the equations above. Furthermore, the numerical values of the tunneling exponents are in good agreement with theoretical predictions[13]. These results provide strong evidence that the Luttinger model properly describes the low energy physics of electrons in metallic carbon nanotubes.

#### 4. CONCLUSION AND ACKNOWLEDGEMENTS

In conclusion, nanotubes are a wonderful new system for exploring the physics of the interacting 1D electron gas. We wish to thank R.E. Smalley and his collaborators for providing the nanotube material used in these studies. We also wish to thank Leon Balents, Marvin Cohen, Cees Dekker, Dung-Hai Lee, Steven Louie, and Alex Zettl for constructive interactions. This work was supported by DOE, Basic Energy Sciences, Materials Sciences Division, the  $sp^2$  Materials Initiative.

#### REFERENCES

1. J.W.G. Wildoer *et al.*, *Nature* **391**, 59 (1998); T.W. Odom, J. Huang, P. Kim, & C.M. Lieber, *Nature* **391**, 62 (1998).
2. S. Tans *et al.*, *Nature* **386**, 474 (1997).
3. M. Bockrath *et al.*, *Science* **275**, 1922 (1997).
4. David H. Cobden *et al.*, *Phys. Rev. Lett.* **81**, 681 (1998).
5. Marc Bockrath *et al.*, submitted to *Nature*.
6. S.J. Tans, *et al.*, *Nature* **393**, 49 (1998).
7. S.J. Tans, *et al.*, *Nature* **394**, 761 (1998).
8. A. Bezryadin *et al.*, *Phys. Rev. Lett.* **80**, 4036 (1998).
9. Andreas Thess *et al.*, *Science* **273**, 483 (1996).
10. L.P. Kouwenhoven *et al.*, in *Mesoscopic Electron Transport*, eds. L. P. Kouwenhoven, G. Schon and L. L. Sohn (Kluwer, 1997).
11. Elliot Lieb and Daniel Mattis, *Phys. Rev.* **125**, 164 (1962).
12. M.P.A. Fisher & L. I. Glazman, in *Mesoscopic Electron Transport* eds. L. P. Kouwenhoven, G. Schon and L. L. Sohn (Kluwer, 1997).
13. R. Egger, R. & A. Gogolin, *Phys. Rev. Lett.* **79**, 5082 (1997); C. Kane, L. Balents, L. & M.P.A. Fisher, *Phys. Rev. Lett.* **79**, 5086 (1997).