High Mobility Semiconducting Carbon Nanotubes

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Single-walled carbon nanotubes (SWNTs) – nanometer-diameter wires of pure carbon – have attracted significant interest both for the opportunity to research the basic science of one-dimensional electronic systems as well as for their possible use in nanoelectronics applications. SWNTs may be metallic or semiconducting depending sensitively on how the graphene lattice is wrapped to form the nanotube(*1*). Research into the electronic properties of SWNTs has focused primarily on metallic nanotubes and their excellent conduction properties as ballistic quantum wires(*2*). Initial studies of semiconducting SWNTs showed poorer conduction, due to local conduction barriers – likely caused by defects in the nanotubes(*3*).

Here we report on the growth of clean semiconducting SWNTs via chemical vapor deposition. The individual semiconducting SWNTs have extremely high mobilities, more than an order of magnitude greater than pure silicon at room temperature. In contrast to metallic SWNTs, these semiconducting nanotubes represent an electronically tunable one-dimensional system: the electronic mean-free-paths are tunable from sub-nanometers to microns by application of a gate voltage, corresponding to conductivity tunable from insulating to comparable to copper. These semiconducting SWNTs are hence an ideal laboratory for exploring the basic physics of electrons in one dimension. The high mobility of these SWNTs also lends them to applications involving charge detection, such as memories, and chemical/biochemical sensors.

Devices were prepared on degenerately-doped silicon substrates capped by 500nm of SiO_2. SWNTs were grown on the substrates using chemical vapor deposition at 900ºC, with methane as the feedstock gas. Alignment marks were patterned on the substrate using electron-beam lithography, and SWNTs were located relative to the alignment marks by atomic force microscopy. A second electron-beam lithography step established Cr/Au electrical contacts to individual SWNTs.

Figure 1 shows the conductance G of a 20-micron-long SWNTas a function of voltage V_g applied to the silicon substrate (gate). The overall behavior is that of a p-channel depletion-mode transistor, as previously seen in tubeFET devices(*4, 5*). The mobility μ of the nanotube may be calculated from the slope of the $G(V_g)$ curve:

$$\mu = \frac{L^2}{C_g} \frac{dG}{dV_g}$$

where C_g is the gate capacitance. The gate capacitance was determined to be ~200 aF from low-temperature measurements of the Coulomb blockade. This gives a hole mobility of ~2×10^4 $cm^2/V\cdot s$ at room temperature(*6*), significantly higher than the hole mobility in Si (~450 $cm^2/V\cdot s$). Since the measured $G(V_g)$ may include contributions from the contacts, the measured mobility is a *lower bound* on the true nanotube mobility.

High mobility implies a large conductance change for a small change in the charge in the SWNT. This suggests SWNT transistors would be useful as sensitive charge or chemical detectors. In figure 2 we demonstrate the detection of single electronic charges being inserted and removed from traps in the SiO_2 gate dielectric(*7*).

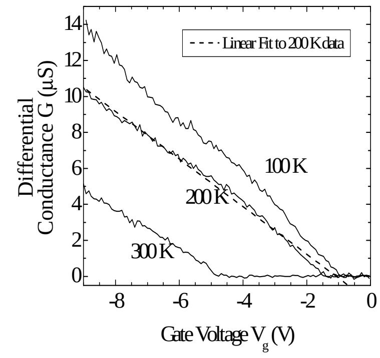

Fig. 1 Current as a function of gate voltage for a 20-micron-long semiconducting SWNT device.

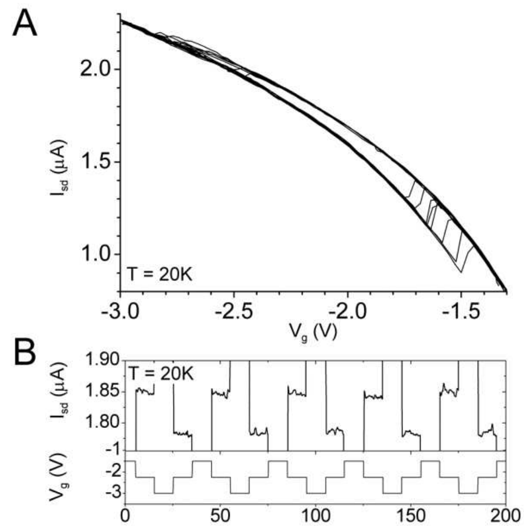

Fig. 2. SWNT single-electron memory. (A) The drain current as a function of gate voltage at a source-drain bias of 500 mV and a temperature of 20K. The gate voltage is swept between -1.3 and -3 V (towards positive eight times, and back negative seven times). Two branches of the curve are evident, corresponding to a difference of one electron in a charge trap near the nanotube. (B) Five read/write cycles of the memory at 20K. The horizontal (time) axis applies to both curves. The memory state was read at a gate voltage of -2.25 V, and written (erased) with pulses of -1.5 V (-3.0 V) to the gate.

REFERENCES

1. M. S. Dresselhaus, G. Dresselhaus, P. C. Eklund, *Science of fullerenes and carbon nanotubes* (Academic Press, San Diego, 1996).
2. A. Bachtold *et al.*, *Physical Review Letters* **84**, 6082-6085 (2000).
3. P. L. McEuen, M. Bockrath, D. H. Cobden, Y.-G. Yoon, S. G. Louie, *Physical Review Letters* **83**, 5098 (1999).
4. S. J. Tans, R. M. Verschueren, C. Dekker, *Nature* **393**, 49-52 (1998).
5. R. Martel, T. Schmidt, H. R. Shea, T. Hertel, P. Avouris, *Applied Physics Letters* **73**, 2447-9 (1998).
6. T. Dürkop, T. Brintlinger, M. S. Fuhrer, in *Structural and Electronic Properties of Molecular Nanostructures* H. Kuzmany, J. Fink, M. Mehring, S. Roth, Eds. (AIP Conference Proceedings, New York, 2002) pp. 242-246.
7. M. S. Fuhrer, B. M. Kim, T. Dürkop, T. Brintlinger, *Nano Letters* **2**, 755 (2002).