Final Report Submitted to the

Air Force Office of Scientific Research

for research on

Manipulating Local Electronic Properties of Carbon Nanotubes

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Carbon nanotubes have many emerging technological uses, from strengthening lightweight composite materials to reducing voltage requirements in field-emission displays. Companies such as IBM and Intel have substantial research efforts aimed at the more complex task of building transistors and computer processors from nanotubes. Research under this proposal addresses one of the important requirements for achieving that vision: understanding and modifying electron flow in one-dimensional systems (carbon nanotubes) by local gating, to create transistors. We have succeeded in making transistors on nanotubes using narrow top-gates, and have also developed a method to dynamically measure local heating in nanowires.

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Objectives:

Carbon nanotubes have many emerging technological uses, from strengthening lightweight composite materials to reducing voltage requirements in field-emission displays. Companies such as IBM and Intel have substantial research efforts aimed at the more complex task of building transistors and computer processors from nanotubes. Research under this proposal addresses one of the important requirements for achieving that vision: understanding and modifying electron flow in one-dimensional systems (carbon nanotubes) by local gating, to create transistors.

Status of effort:

As of the end of funding, Feb 29, 2008, funding had been going for nearly three years on this project. The nominal start date was April 1, 2005, but the issue date by the AFOSR was June 10, 2005, and funding was activated at Stanford on July 1, 2005.

Accomplishments:

1. Locally-gated nanotube devices have been fabricated 100 or more at a time, in a manner that may lead the way to scalable devices. After growth of nanotubes at an array of locations, contacts and gates are deposited without a time-consuming and laborious search for nanotubes. Our yield of working devices is roughly 30%. We expect this could be enhanced dramatically by using tailored catalyst (iron nanoparticles) and any of several established techniques for aligning nanotubes during growth (e.g. electric field, gas flow.)

2. The silicon substrates we (and many of our colleagues) were using as large-area gates for nanotubes were shown to contribute to hysteresis in electrical measurements at low temperature due to insufficient doping. Also, oxides grown by the wafer vendors had very low breakdown voltage. We obtained more heavily doped substrates (5 milliohm cm) and learned to grow our own high-quality oxides at the Stanford Nanofabrication Facility. This has benefited projects on both my AFOSR grants, as well as early work on the newly-exciting material graphene (a single sheet of graphite.)

3. Processes for locally gating nanotubes have been transferred from facilities at Hitachi Global Storage Technologies (where AFOSR-supported graduate student Joseph Sulpizio developed these processes together with Hitachi scientist Zvonimir Bandic.) This was necessary because fab facilities at Hitachi were taken down for months when they moved their lab, and those facilities are now less accessible for us. Steps we've taken include:

a. Purchasing and installing a used scanning electron microscope (SEM) together with two Stanford Material Science research groups.

b. Setting up e-beam lithography capability on this SEM, and achieving 30 nanometer features with 100 nanometer alignment, plus making large arrays over a 4" wafer in an automated manner. These are the requirements for the devices we're making.

c. Developing etching and metal deposition processes in the Goldhaber-Gordon lab and at the Stanford Nanofabrication Facility.

Joseph Sulpizio has been directly responsible for all of these developments.

4. A new cryostat was set up for measurement of the nanotube devices, and has been tested by measurement of low-disorder suspended nanotube devices in collaboration with the lab of Hongjie Dai (the major pioneer of our CVD method of nanotube growth.) Charis Quay has been primarily responsible for these steps.

5. Successful top-gating of graphene, a novel material consisting of a single layer of carbon atoms

Personnel supported or associated with work:

Principal Investigator:

David Goldhaber-Gordon, Assistant Professor of Physics

Graduate students (external fellowships supplemented):

Charis Quay, Ph.D. student in Physics: working on nanotube transistors and nanotube variants: "peapods". Graduated Dec. 2007.

Joseph Sulpizio, 5^{th} year in Physics: working on nanotube transistors.

Publications or notable interactions:

C.H.L. Quay, John Cumings, S.J. Gamble, A. Yazdani, R. de Picciotto, H. Kataura, and D. G.-G., "Transport properties of carbon nanotube C_{60} peapods", *Phys. Rev. B* **76**, 073404/1–5 (2007).
C.H.L. Quay, John Cumings, Sara Gamble, R. de Picciotto, H. Kataura, and D. G.-G., "Magnetic field dependence of the spin-1/2 and spin-1 Kondo effects in a quantum dot", *Phys. Rev. B*, 245311/1–5 (2007).
J.A. Sulpizio, Z.Z. Bandic, and D. Goldhaber-Gordon, "Nanofabrication of top-gated carbon nanotube-based transistors: Probing electron-electron interactions in one-dimensional systems", *Journal of Mat. Res.* 21 2916-21 (2006).
T. Brintlinger, Yi Qi, K.H. Baloch, D. G.-G., and John Cumings, "Electron Thermal Microscopy", *Nano Letters* 8, 582 (2008).

New discoveries since Sep 2007 progress report:

Quantum dot behavior in electron flow through graphene nanoribbons (in collaboration with Hongjie Dai, Stanford Chemistry).

Honors/Awards:

2002 AFOSR Presidential Early Career Award in Science and Engineering (PECASE) (*actually awarded 2004*). Awarded to two early-career scientists or engineers per year.

2004 David and Lucille Packard Fellow. 16 awarded nationwide to early-career faculty across all fields of science and engineering.

2003 Alfred P. Sloan Foundation Fellowship

2004 Research Corporation Research Innovation Award

2004 Named Co-Director (with Kam Moler) of NSF-Stanford-IBM Nanoscale Science and Engineering Center: “Center for Probing the Nanoscale”

2006 National Academy of Sciences Award for Initiatives in Research

2007 Hellman Faculty Scholar